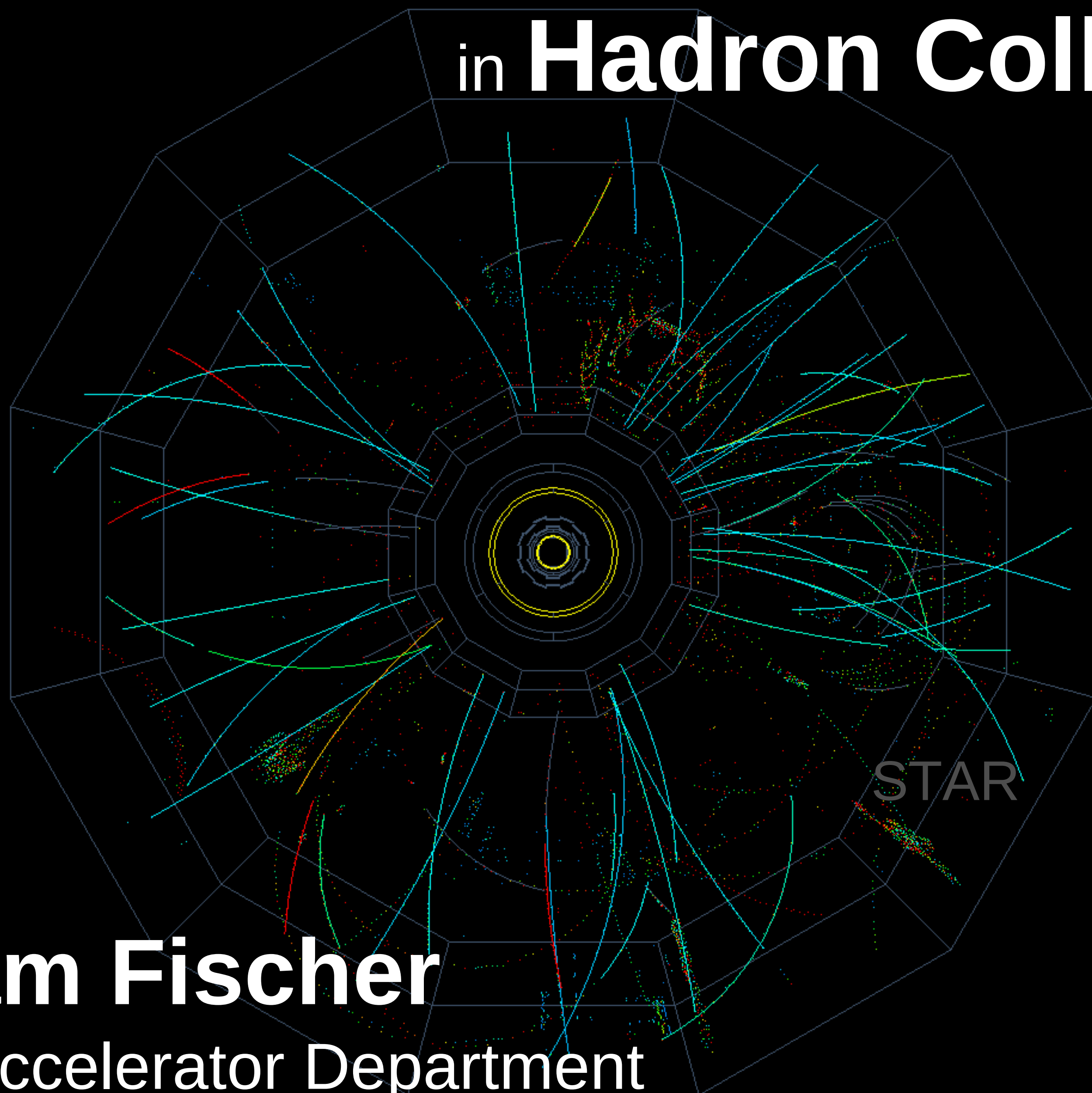
The Quest for **High Luminosity** in **Hadron Colliders**



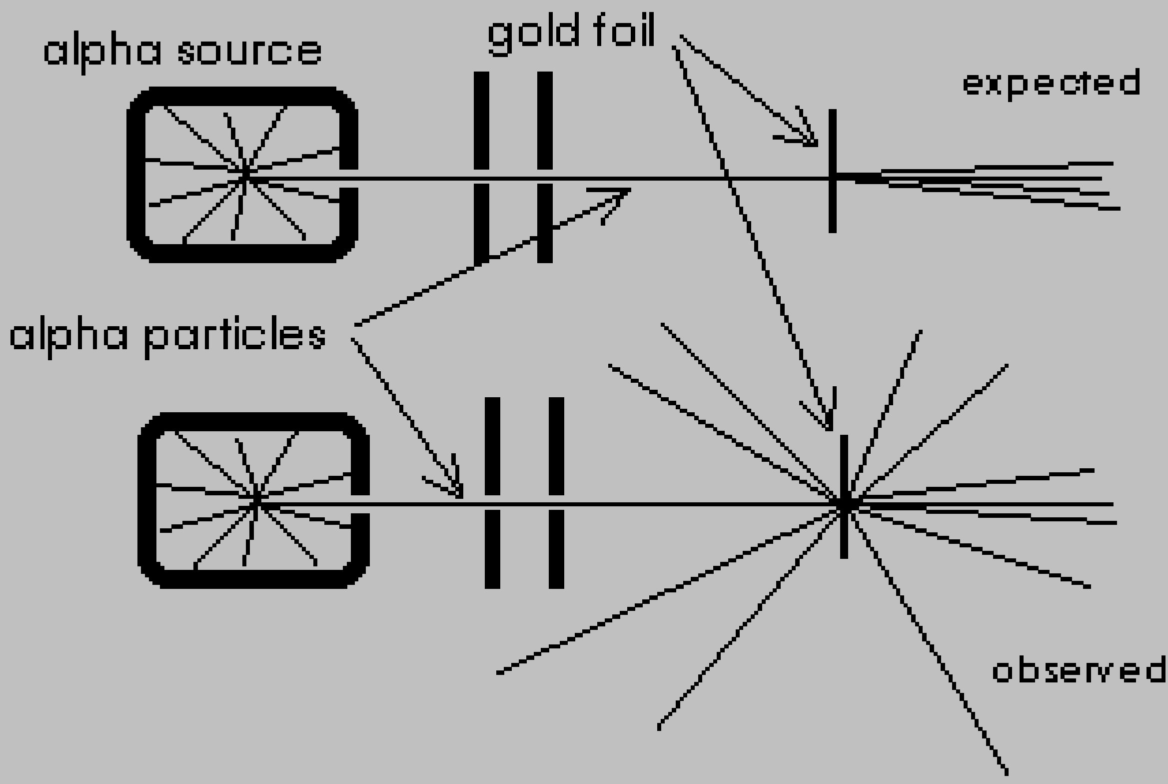
Wolfram Fischer
Collider-Accelerator Department

1. What’s in the title

2. A short history of hadron colliders

3. Limits at RHIC

Production and music by Jeffery Mitchell.
Simulation provided by the UrQMD Collaboration.




Ernest Rutherford
(1871-1937)

Geiger, Marsden, Rutherford 1909

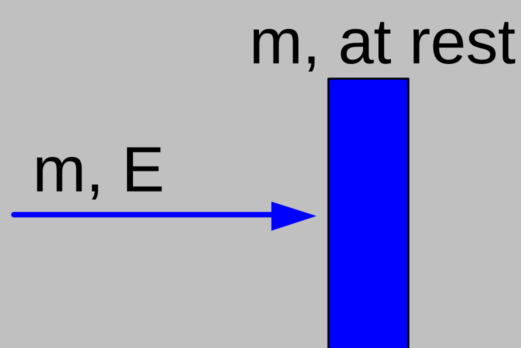
Two main parameters in collision experiments:

1. Energy
   - de Broglie wave length $\lambda = h/p$ of projectile sets limit for spatial resolution
   - Rest mass of new particles $m_0c^2 < E_{cm}$

2. Event rate [$\propto$ luminosity]
   - Event distributions not uniform in space
   - Rare events

Center-of-Mass Energy E_{cm}

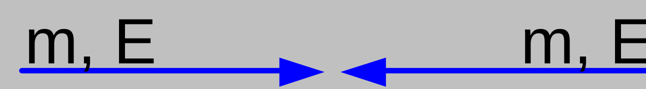
Fixed target



$E_{cm} \approx \sqrt{2\, E\, mc^2}$ $(E \quad mc^2)$

2000 TeV p on p at rest

Collider



$E_{cm} = 2E$

1TeV p on 1TeV p (Tevatron now)

Approximate rest mass of selected particles [10^{-30} kg]

Leptons fundamental particles		**Hadrons** made of quarks and gluons	
Electron $e^+ e^-$	Muon $\mu^+ \mu^-$	Proton $p^+ \bar{p}$	Gold ion Au^{79+}
1	200	1 700	335 000
Radiate at high energies	difficult to make for colliders	**allow largest center-of-mass energies**	

1 GeV proton energy gain
=
acceleration through
1 billion volts

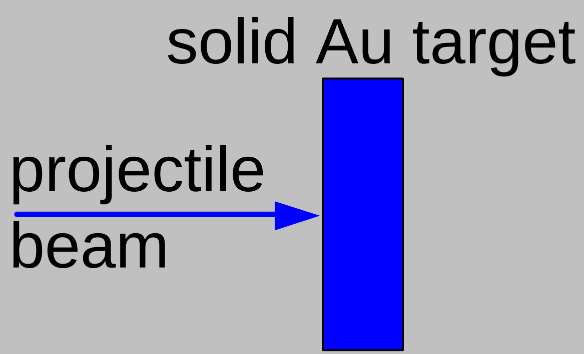
Hadron colliders so far

Time	Machine	Lab	Particles	Energy [GeV]
1972 – 1983	**ISR**	CERN	p-p, A-A	31
1982 – 1990	**SPS**	CERN	p-$\bar{p}$	315
1988 – 2009	**Tevatron**	Fermilab	p-$\bar{p}$	980
1992 – 2007	**HERA**	DESY	$e^{+/-}$↑-p	30-920
2000 –	**RHIC**	BNL	p↑-p↑, A-A	250, 20 000
2007 –	**LHC**	CERN	p-p, A-A	7 000, 580 000

Colliders are some of the largest, most complex research tools

Event rate of colliders is much lower than event rate of fixed target experiments

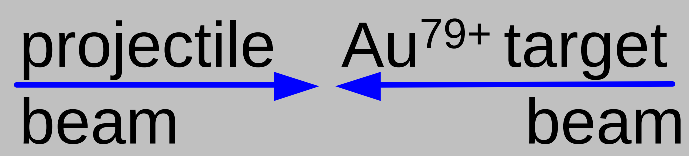
Fixed target



target density

$\rho \approx 5\times10^{28}$ nuclei/m^3

Collider

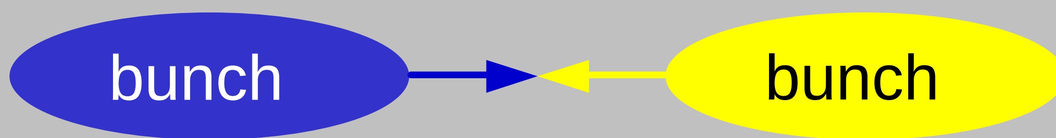


target density

$\rho \approx 10^{16}$ nuclei/m^3

Density of a beam target is <u>many</u> orders of magnitude lower than density of a fixed target

High event rate requires
beam bunches of high density, that collide often



Event rate for certain process [s^{-1}]

$$\frac{dN}{dt} = s_N L$$

Luminosity [$cm^{-2}s^{-1}$]

Only depends on
- number of particles in beam
- beam size
- collision frequency

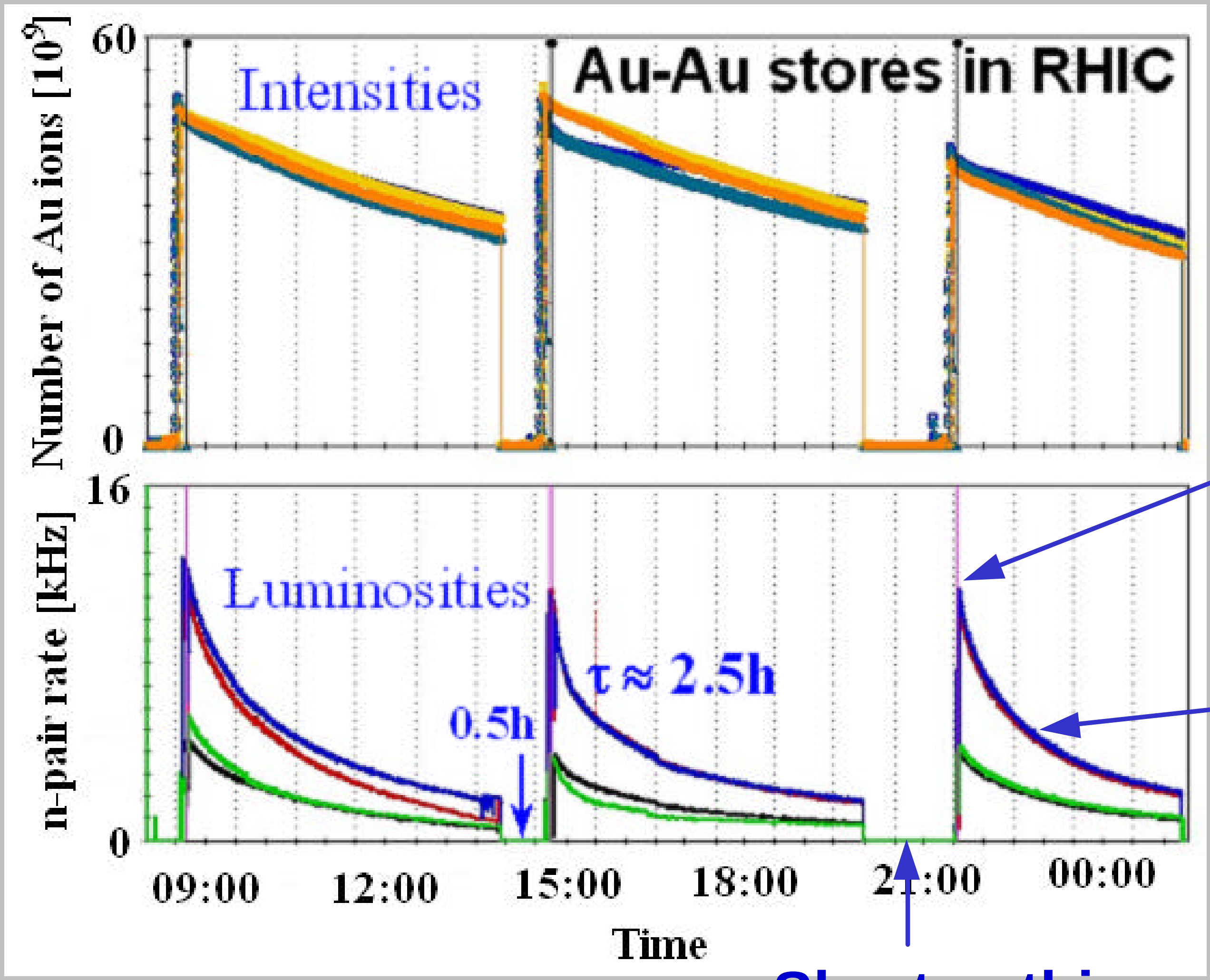
Cross section for process [cm^2]

no of bunches **particles per bunch**

$$L(t) = \frac{1}{4p} f_0 N \frac{n^2(t)}{s^2_{rms}(t)}$$

rms beam size,
shrinks with Ög

f_0 – revolution frequency (constant for given machine)



Maximize this

Flatten this

Shorten this

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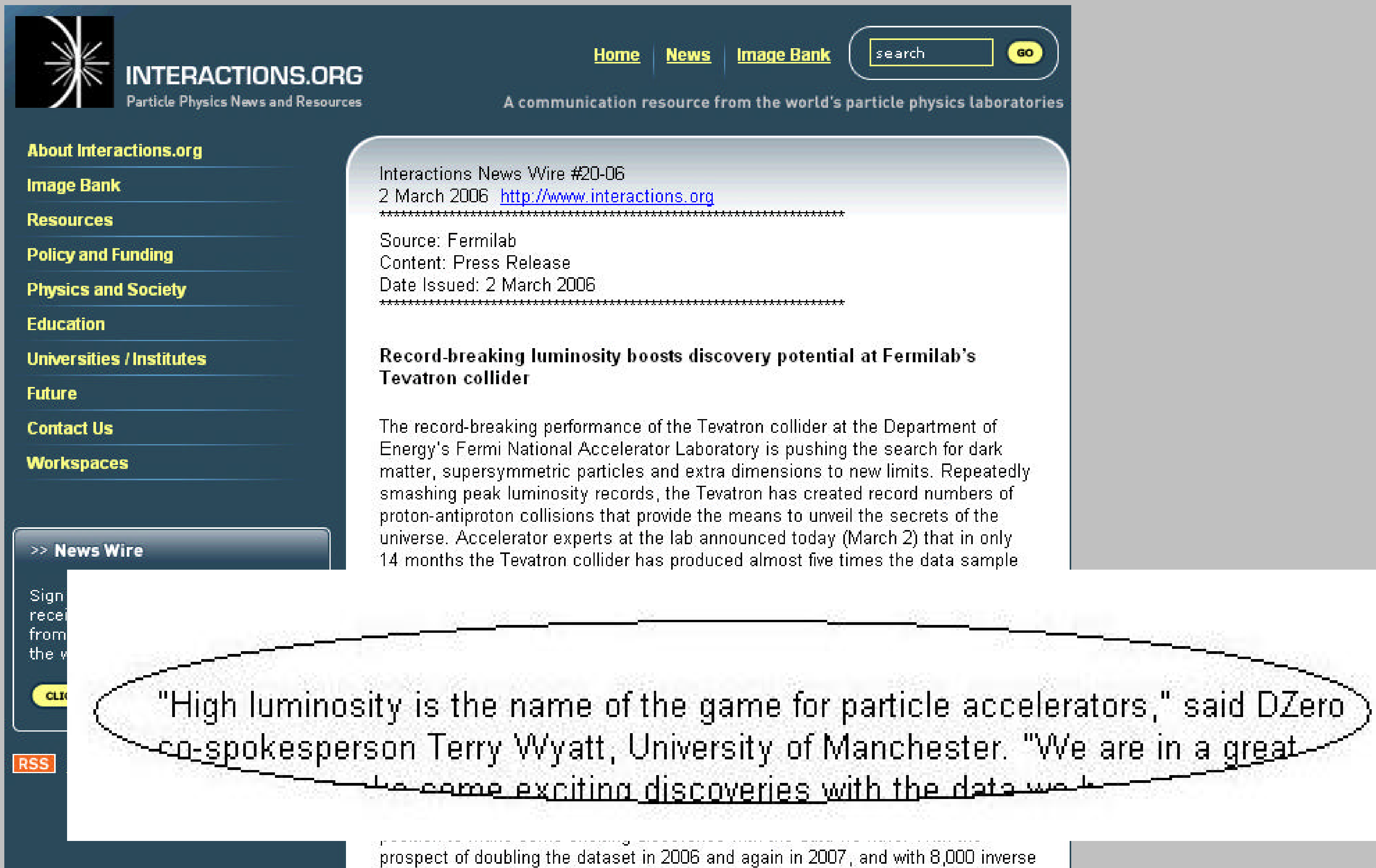
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RSS

Interactions News Wire #20-06
2 March 2006 http://www.interactions.org
****

Source: Fermilab
Content: Press Release
Date Issued: 2 March 2006
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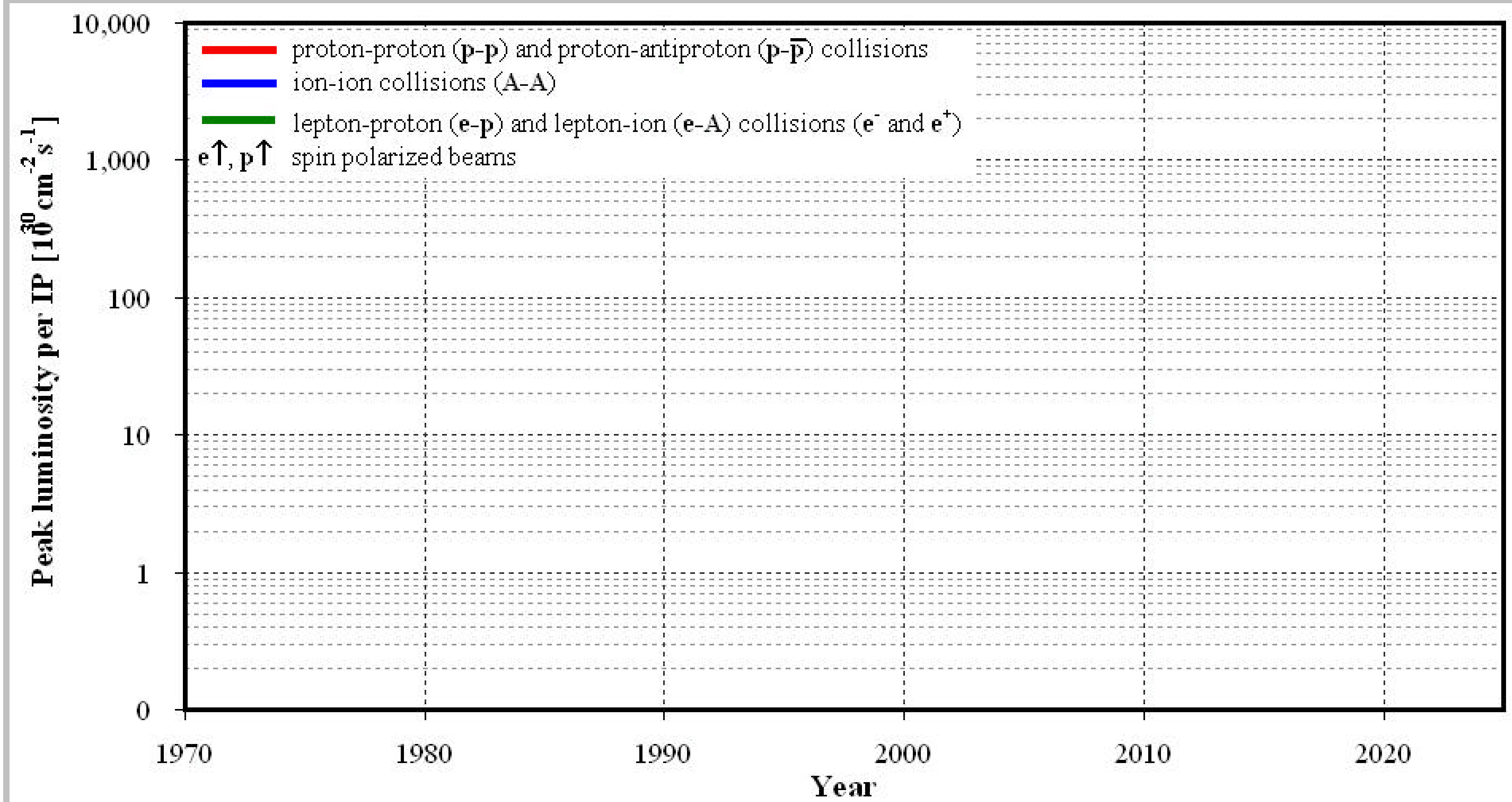
Record-breaking luminosity boosts discovery potential at Fermilab's Tevatron collider

The record-breaking performance of the Tevatron collider at the Department of Energy's Fermi National Accelerator Laboratory is pushing the search for dark matter, supersymmetric particles and extra dimensions to new limits. Repeatedly smashing peak luminosity records, the Tevatron has created record numbers of proton-antiproton collisions that provide the means to unveil the secrets of the universe. Accelerator experts at the lab announced today (March 2) that in only 14 months the Tevatron collider has produced almost five times the data sample

"High luminosity is the name of the game for particle accelerators," said DZero co-spokesperson Terry Wyatt, University of Manchester. "We are in a great ... exciting discoveries with the data we h...

prospect of doubling the dataset in 2006 and again in 2007, and with 8,000 inverse

The Quest for **High Luminosity** in **Hadron Colliders**



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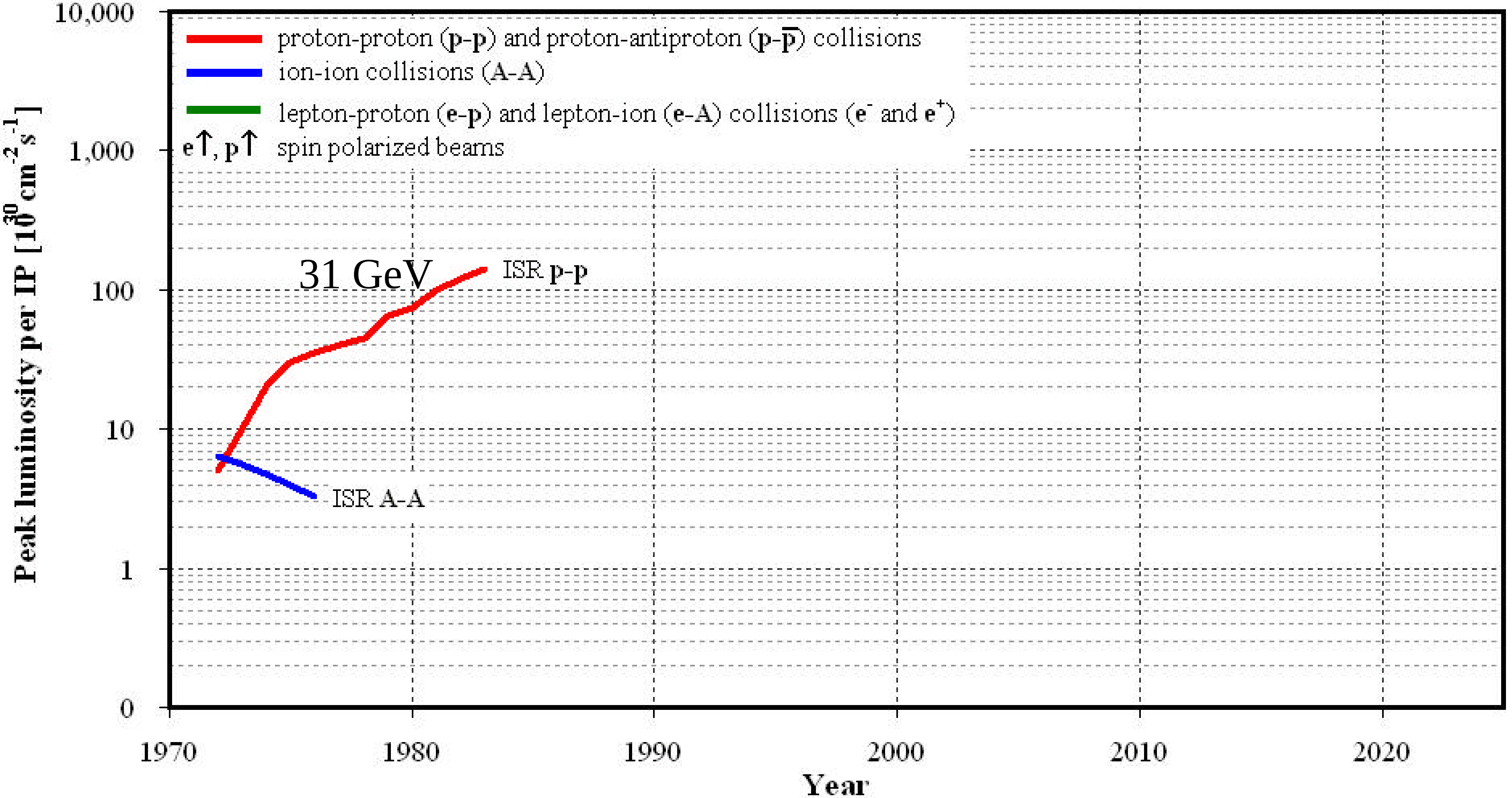
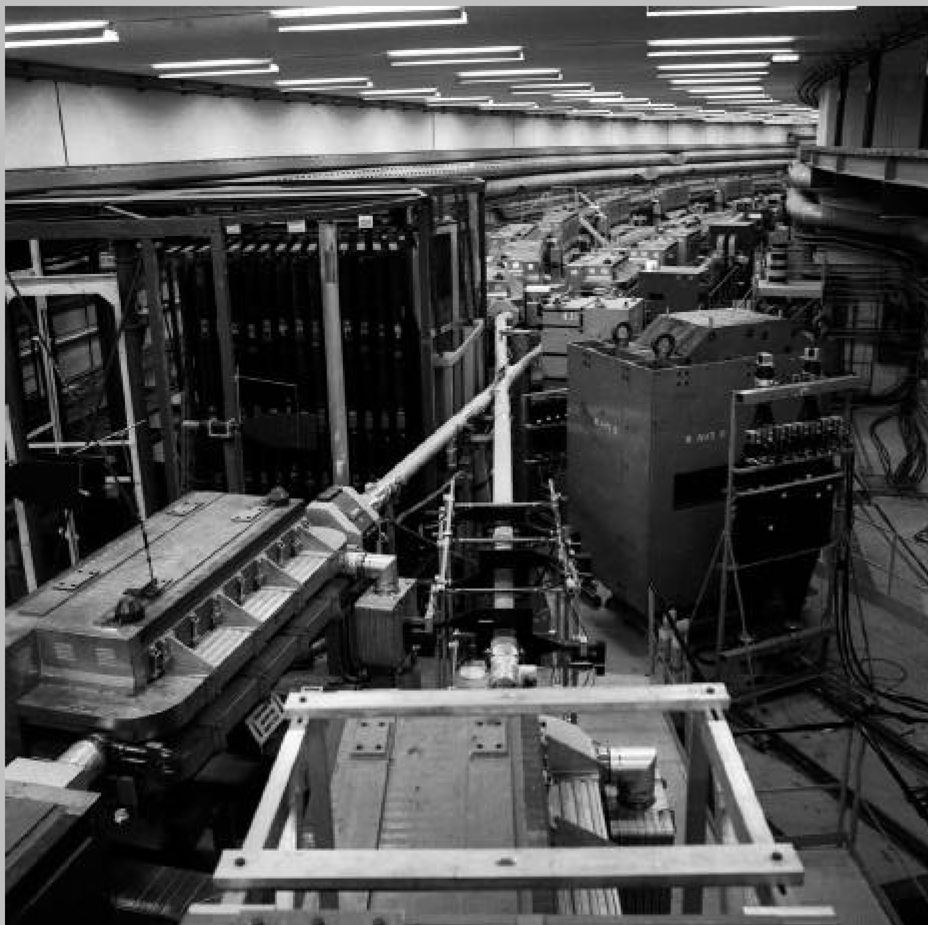


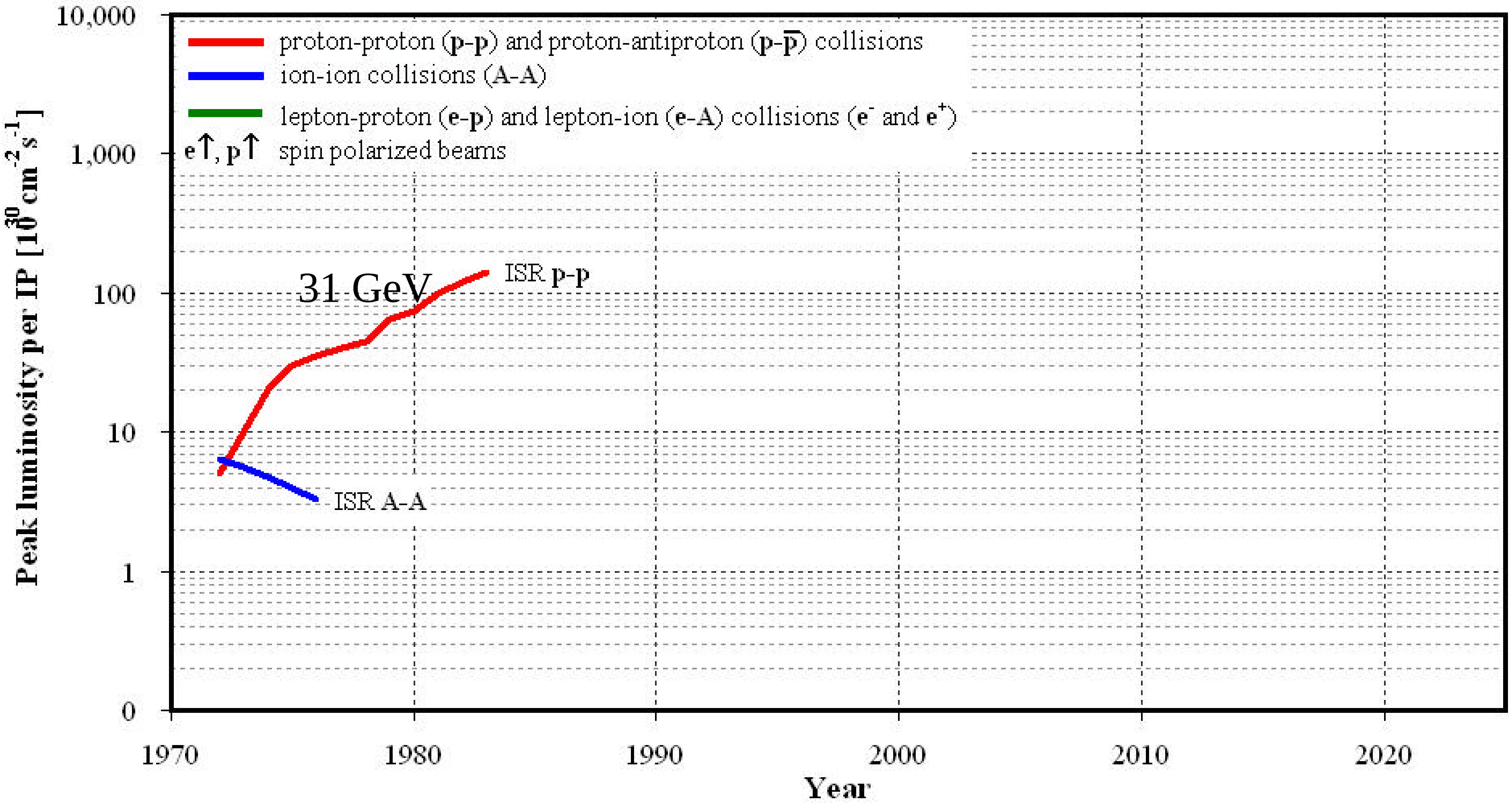
CERN – Intersecting Storage Rings (ISR)



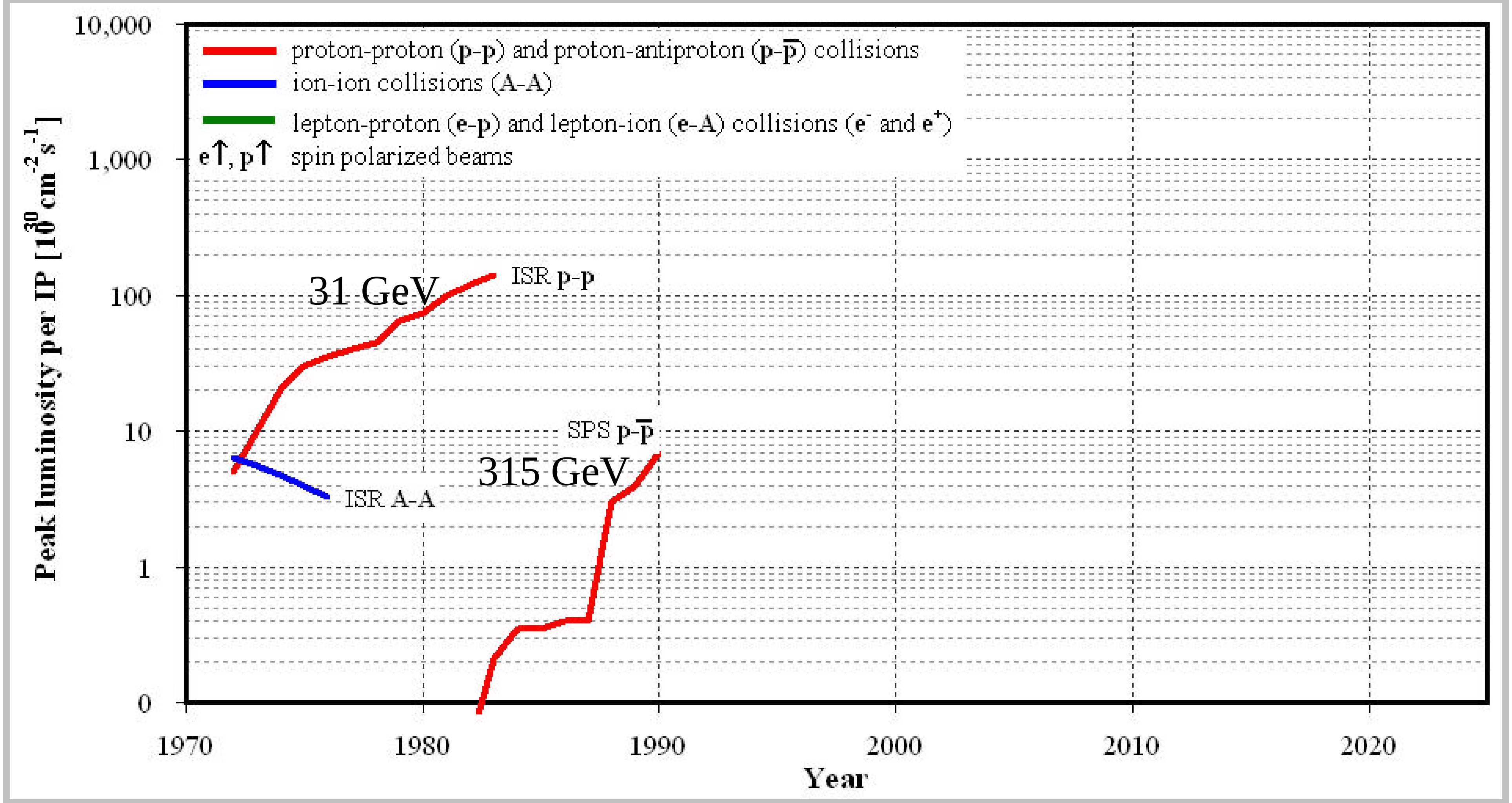
Time	1972-1983
Circumference [km]	0.95
Energy [GeV]	31.2
Particles	p-p p-$\bar{p}$ p-d He-He
Peak luminosity [$10^{30}cm^{-2}s^{-1}$]	**140**

First hadron collider,
up to 60A beam current, luminosity record held until 2005

The Quest for High Luminosity in Hadron Colliders



The Quest for High Luminosity in Hadron Colliders



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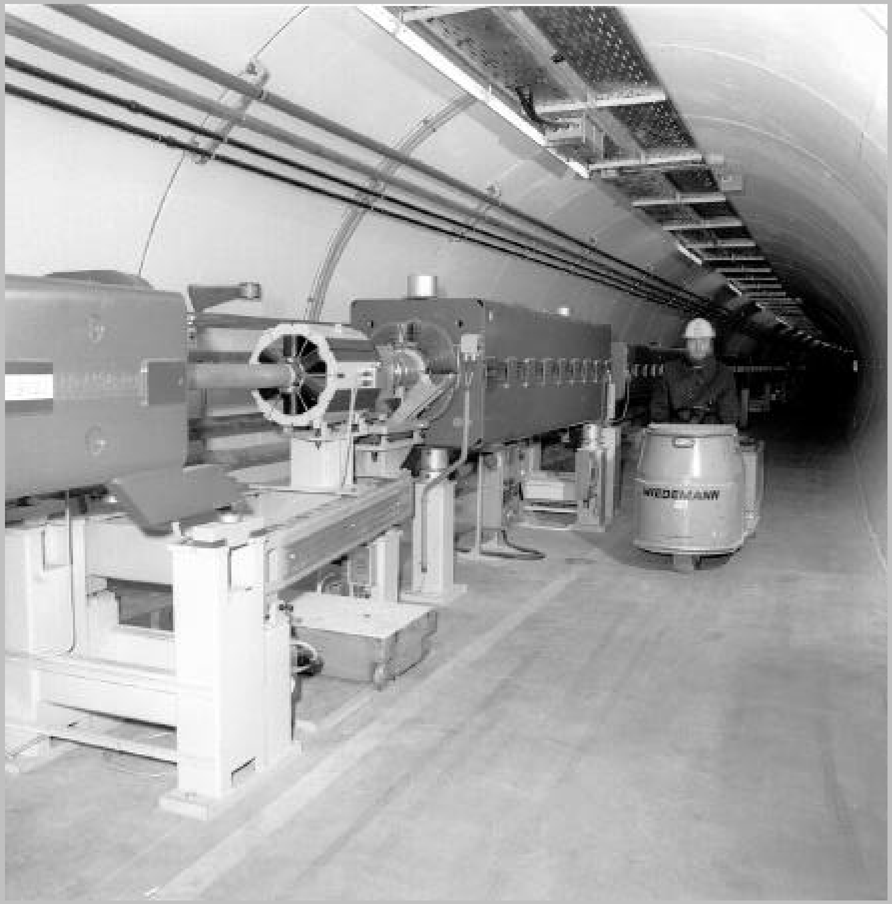
CERN – Super Proton Synchrotron (SPS)



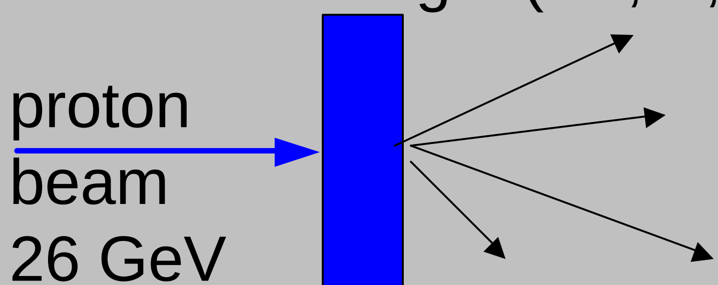
Time	1982-1990
Circumference [km]	6.8
Energy [GeV]	315
Particles	p-$\bar{p}$
Peak luminosity [10^{30}cm^{-2}s^{-1}]	**7**

First use of anti-protons in collider, both beams in same beam pipe

CERN – Super Proton Synchrotron (SPS)

$$L(t) = \frac{1}{4\pi} f_0 N \frac{n_1(t)n_2(t)}{\sigma^2(t)}$$

Anti-proton production



Debris contains anti-protons, need to

1. Filter out anti-protons
2. Increase anti-proton density (stochastic cooling)
3. Store anti-protons

About 1 anti-proton for 1 million protons

Anti-proton storage vessel

Anti-proton production rate is main luminosity limit

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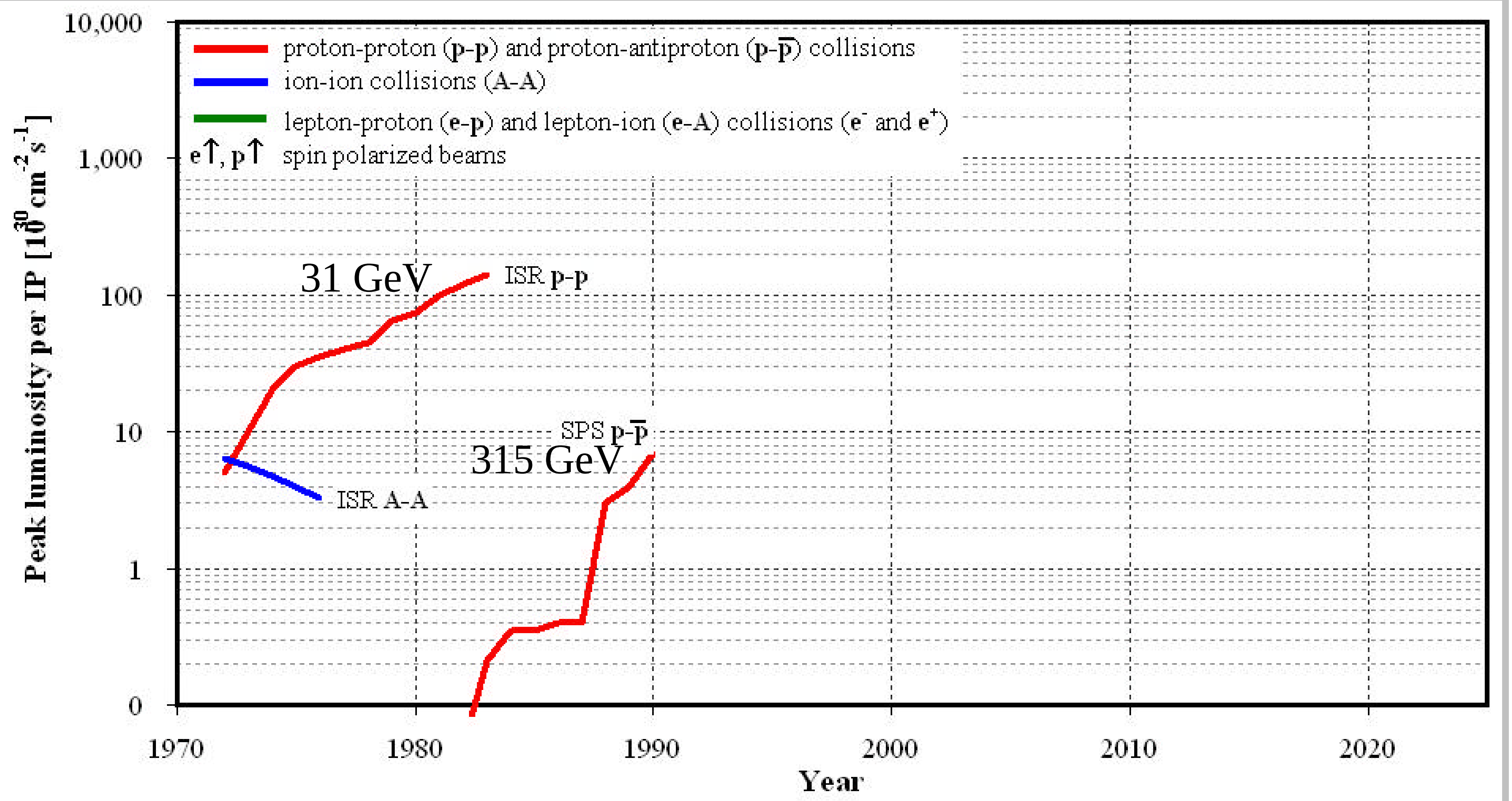
CERN – SPS

1984 Nobel Prize to Carlo Rubbia (left) & Simon van der Meer

For discovery of W and Z

van der Meer invented stochastic cooling

The Quest for High Luminosity in Hadron Colliders



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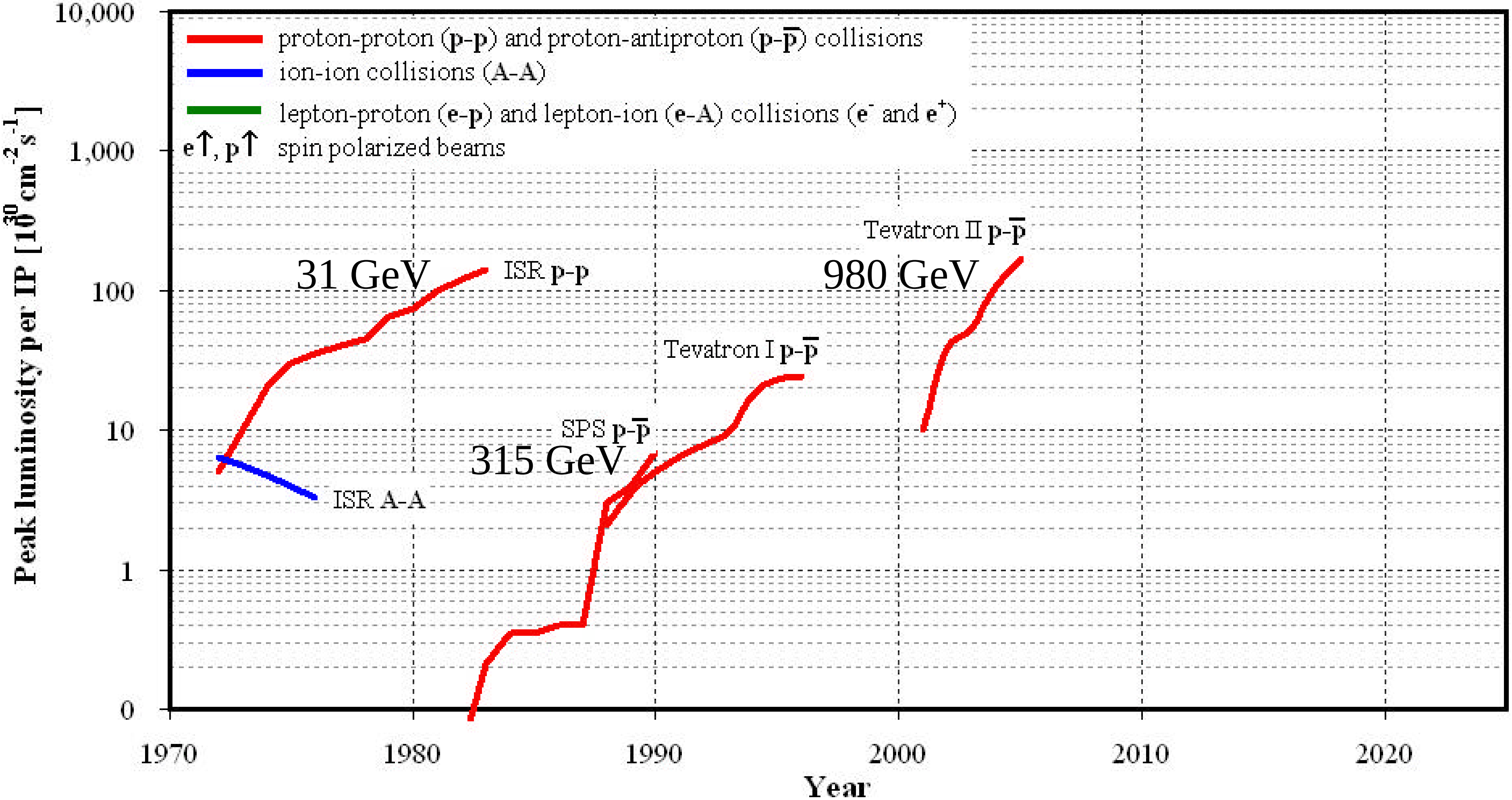
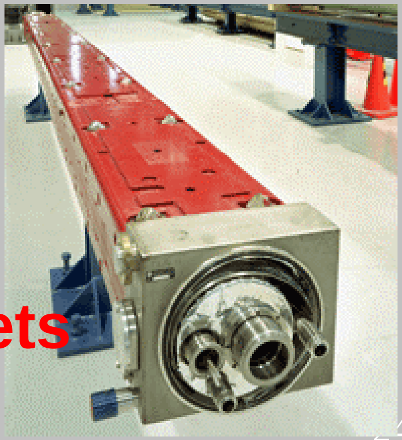


Fermilab – Tevatron

Time	1988-2009
Circumference [km]	6.3
Energy [GeV]	980
Particles	p-$\bar{p}$
Peak luminosity [$10^{30}cm^{-2}s^{-1}$]	**170**



First collider with superconducting main magnets

Fermilab – Tevatron

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Top quark discovered with the Tevatron in 1995

Anti-proton production rate is again main luminosity limit

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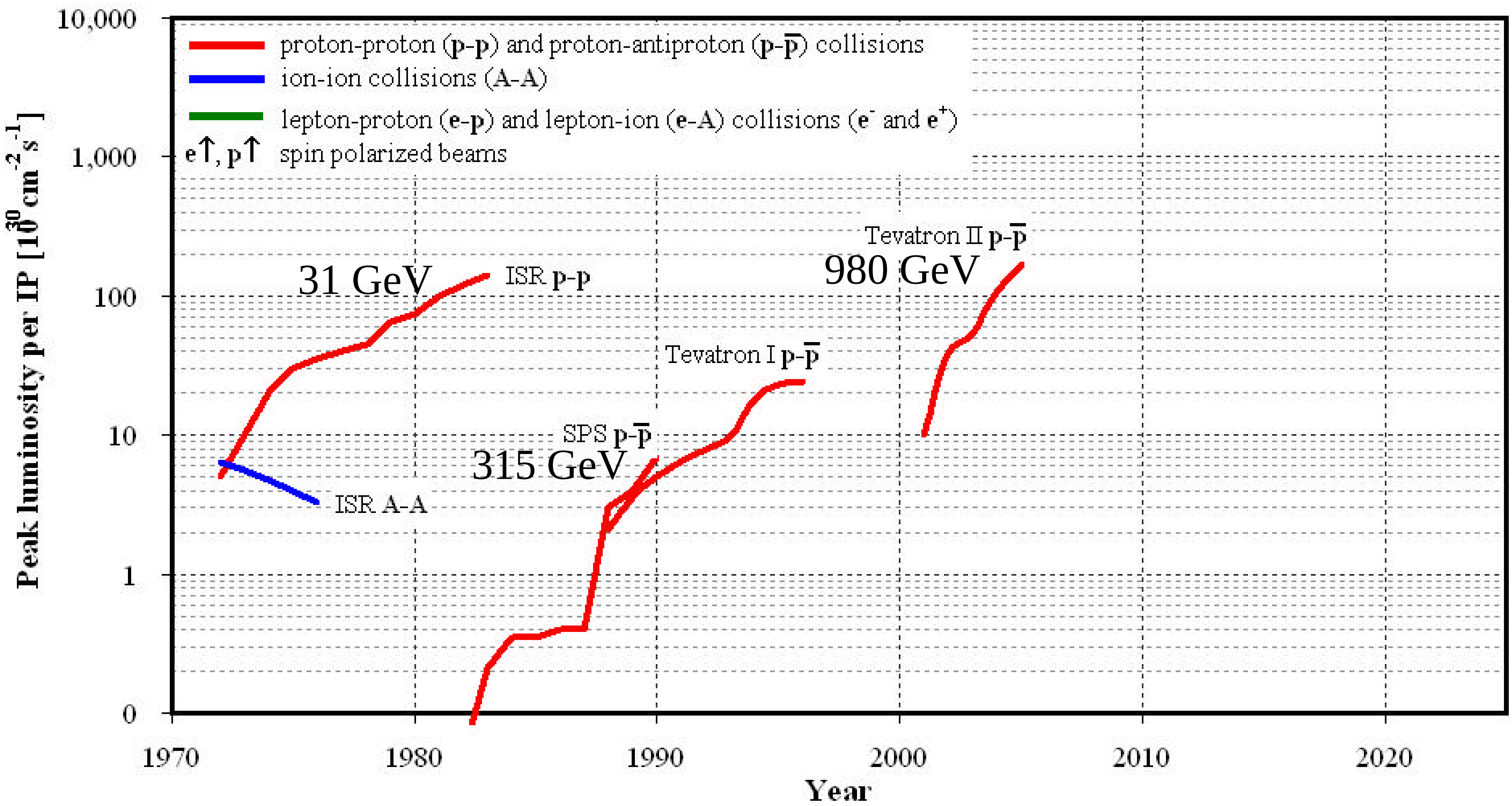
The Quest for High Luminosity in Hadron Colliders



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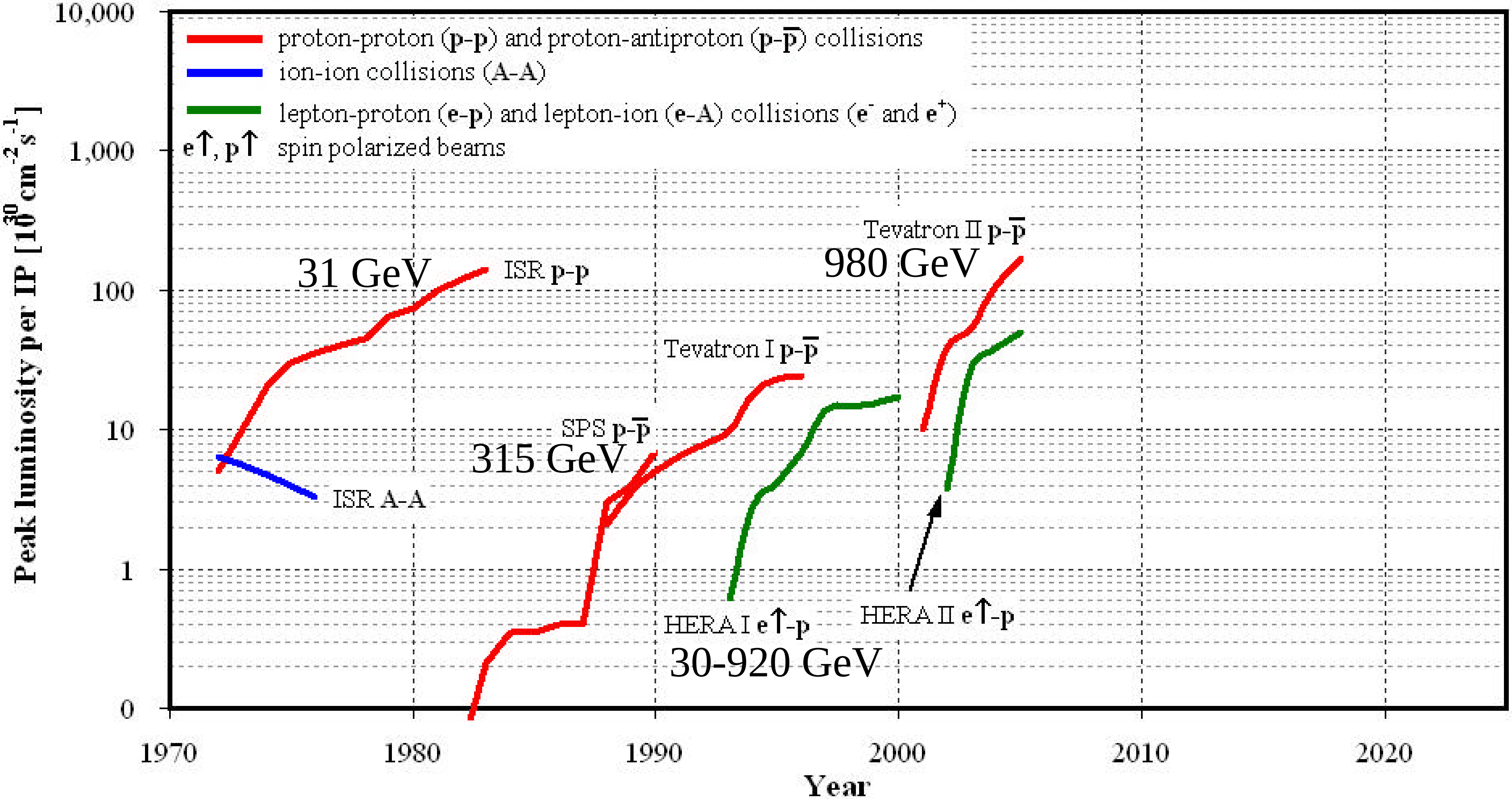
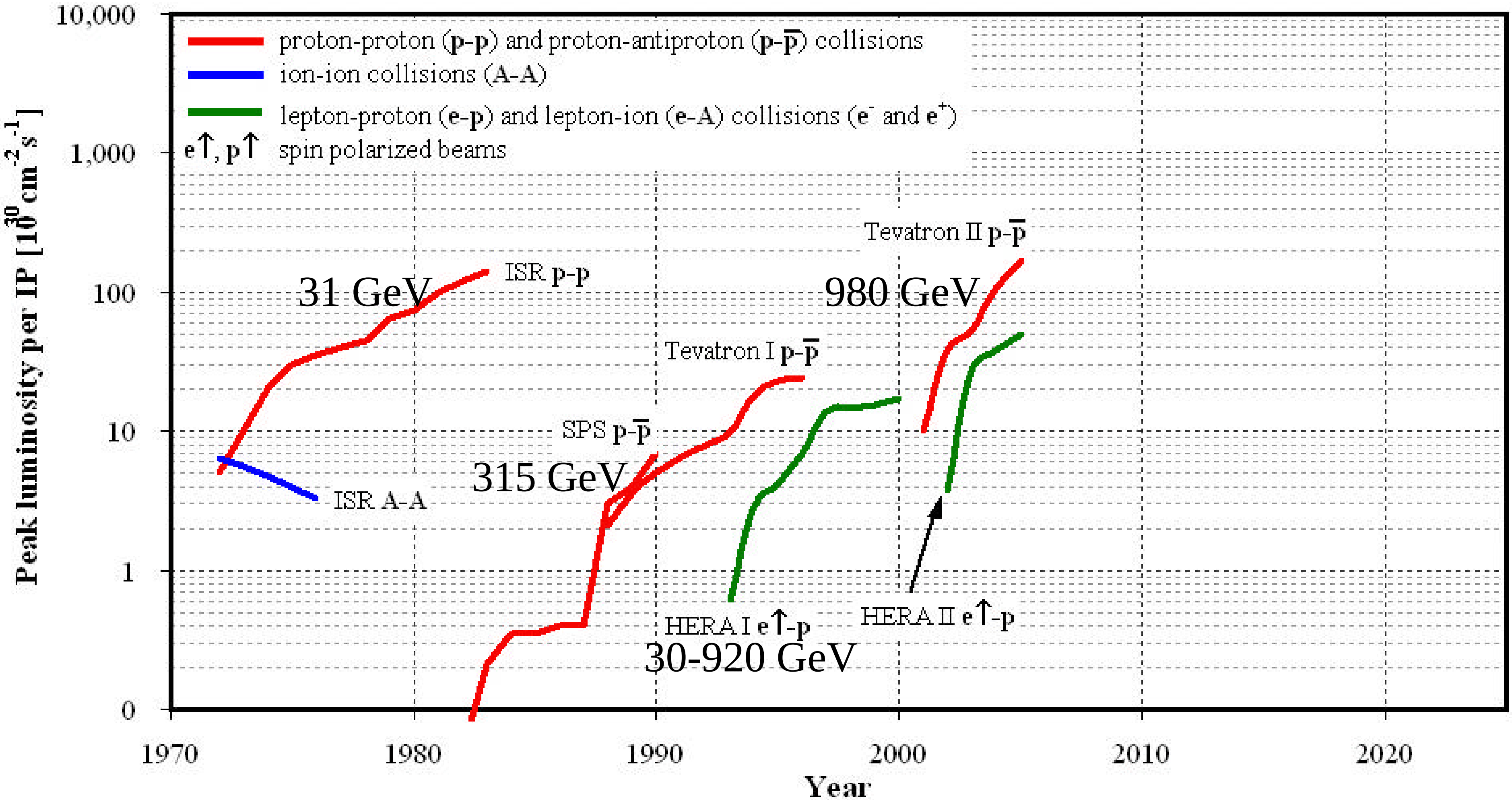


DESY – HERA

Time	1992-2007
Circumference [km]	6.3
Energy [GeV]	920-30
Particles	p-e^+/e^-↑
Peak luminosity [10^{30}cm^{-2}s^{-1}]	**75**

First electron/positron – proton collider

The Quest for High Luminosity in Hadron Colliders



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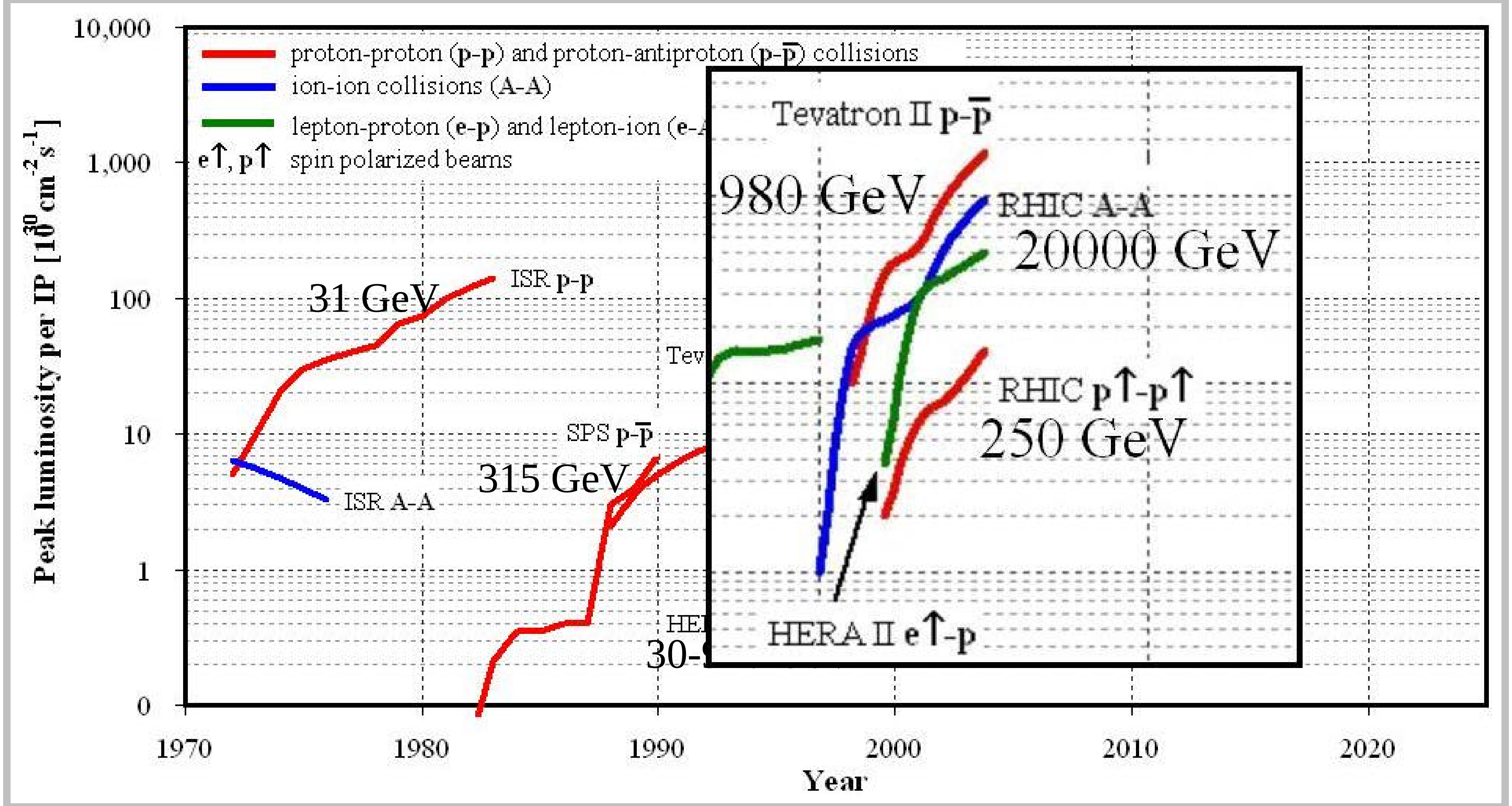


BNL – Relativistic Heavy Ion Collider (RHIC)

Time	2000-
Circumference [km]	3.8
Energy [GeV]	20000 Au 250 p↑
Particles	Au-Au d-Au Cu-Cu p↑-p↑
Peak luminosity [10^{30}cm^{-2}s^{-1}]	**100 (so far)**

First heavy ion collider
First collider of spin polarized protons
Unparalleled flexibility (species, energy)

RHIC

2 separated rings allow for large flexibility (including different species in the 2 rings)

rf stations – keep particles in bunches

RHIC discovered new state of matter

Contacts: Karen McNulty Walsh, (631) 344-8350 or Mona S. Rowe, (631) 344-5056

Print-friendly E-mail Article

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsor
Department of Energy is producing historic
said Secretary of Energy Samuel Bodman, a
chemical engineer. "The DOE is the principa
funder of basic research in the physical sci
including nuclear and high-energy physics.
today's announcement we see that investr
off."

"The truly stunning finding at RHIC that th
state of matter created in the collisions of
more like a liquid than a gas gives us a pro
insight into the earliest moments of the uni
said Dr. Raymond L. Orbach, Director of th
Office of Science.

Also of great interest to many following progress at RHIC is the emerging

83000 google hits for "RHIC discovery"

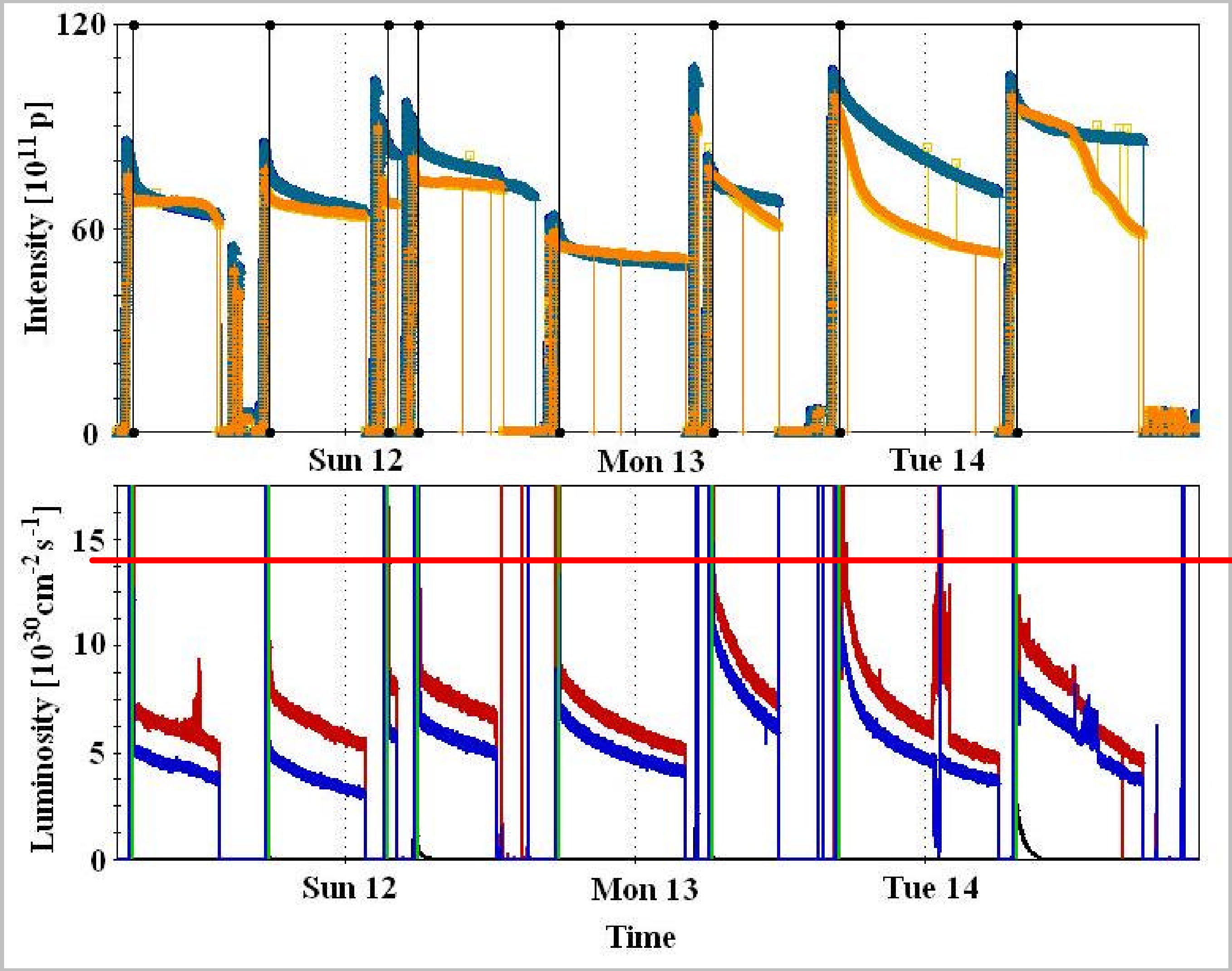
At One Trillion Degrees, Even Gold Turns Into the Sloshiest Liquid

April 19, 2005, Tuesday
By KENNETH CHANG (NYT); Sc
Late Edition - Final, Section F, Page

The New York Times ON THE WEB

DISPLAYING FIRST 50 OF 807 WORDS -It is about a trillion degrees hot and flows like water. Actually, it flows much better than water. Scientists at the Brookhaven National Laboratory on Long Island announced yesterday that experiments at its Relativistic Heavy Ion Collider -- RHIC, for short, and pronounced "rick" -- had produced a state...

RHIC Run-6: polarized protons at 3 or 4 different energies



Last few days of operation

Reached last year's peak rates after 1 week of physics operation

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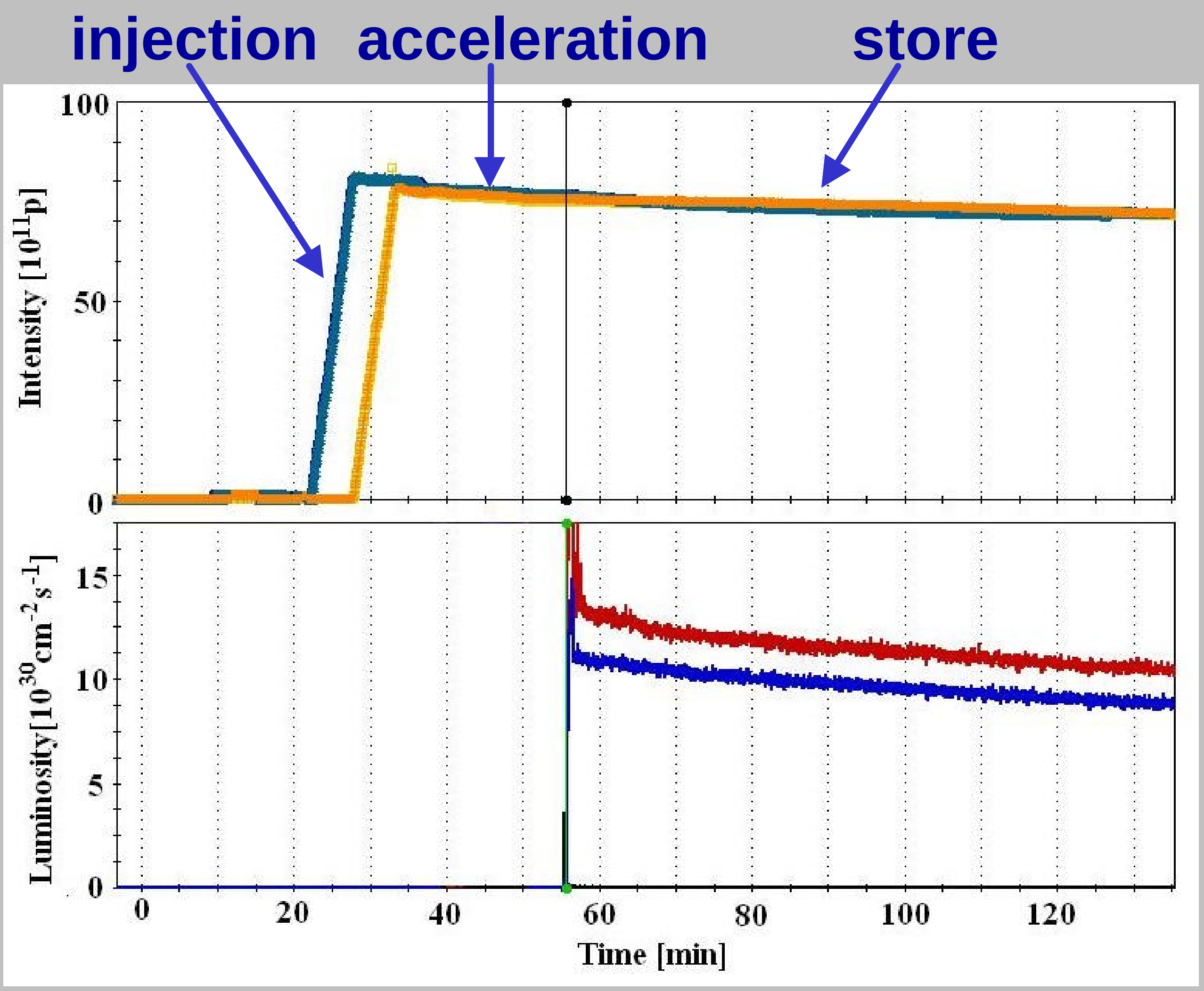
Injection – acceleration – store

Follow limits in the cycle:



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Injectors can limit bunch intensity

$$L(t) = \frac{1}{4p} f_0 N \frac{n^2(t)}{s_{rms}^2(t)}$$

- Not a problem for (unpolarized) protons
- Severe problem for antiprotons

- **Heavy ions for RHIC**
  - Required years of development
  - Many limits from source to AGS
    (space charge, charge exchange, ion-impact desorption, IBS, …)
  - Now RHIC injectors 10x better than next machine (LHC)

- **Polarized protons for RHIC**
  - Unique capabilities
  - Requires snakes in AGS

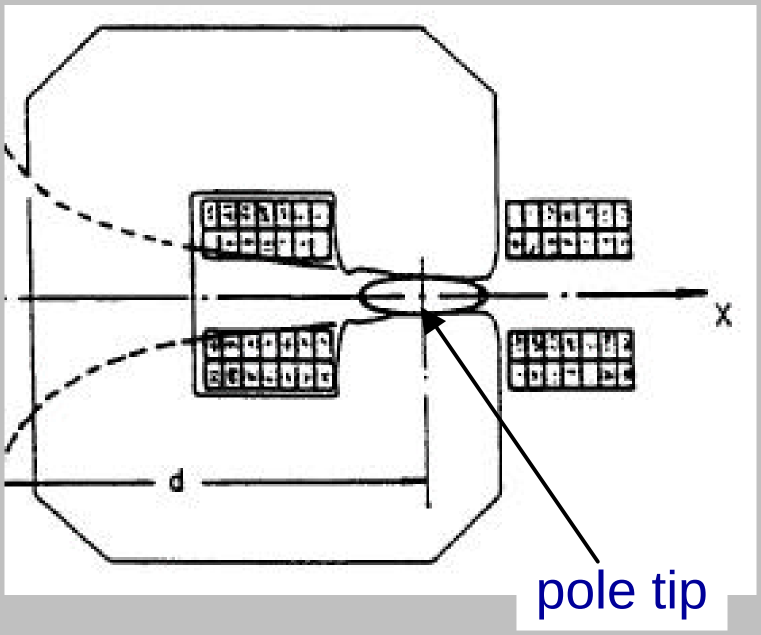
Superconducting helical magnet in AGS – most complex magnet ever built by Superconducting Magnet Division

Nonlinear fields lead to particle loss

Accelerator magnets

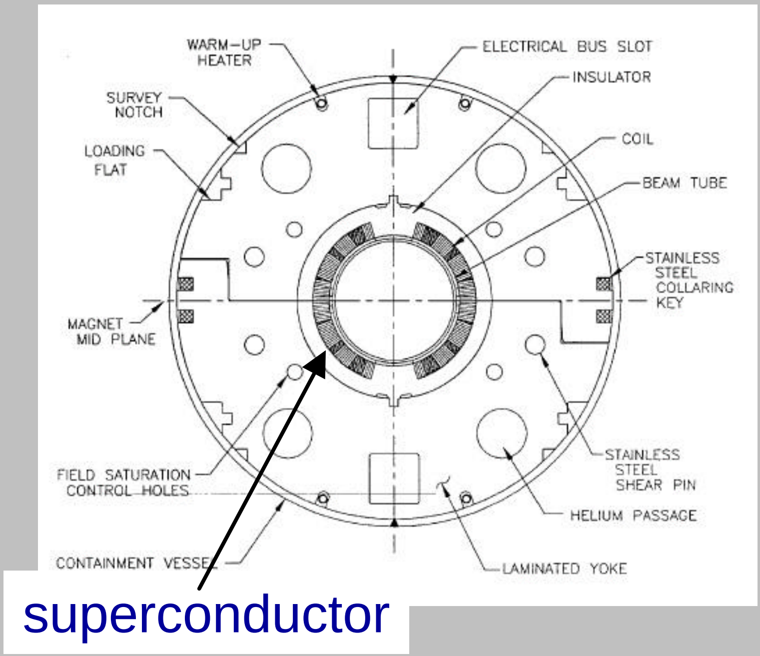
Normal conducting

- Lower fields (~1.5T), limited by iron saturation
- Small field errors, controlled by pole tips



Super conducting

- Higher fields (~5T)
- Larger field errors, from geometry and persistent currents (time dependent!)

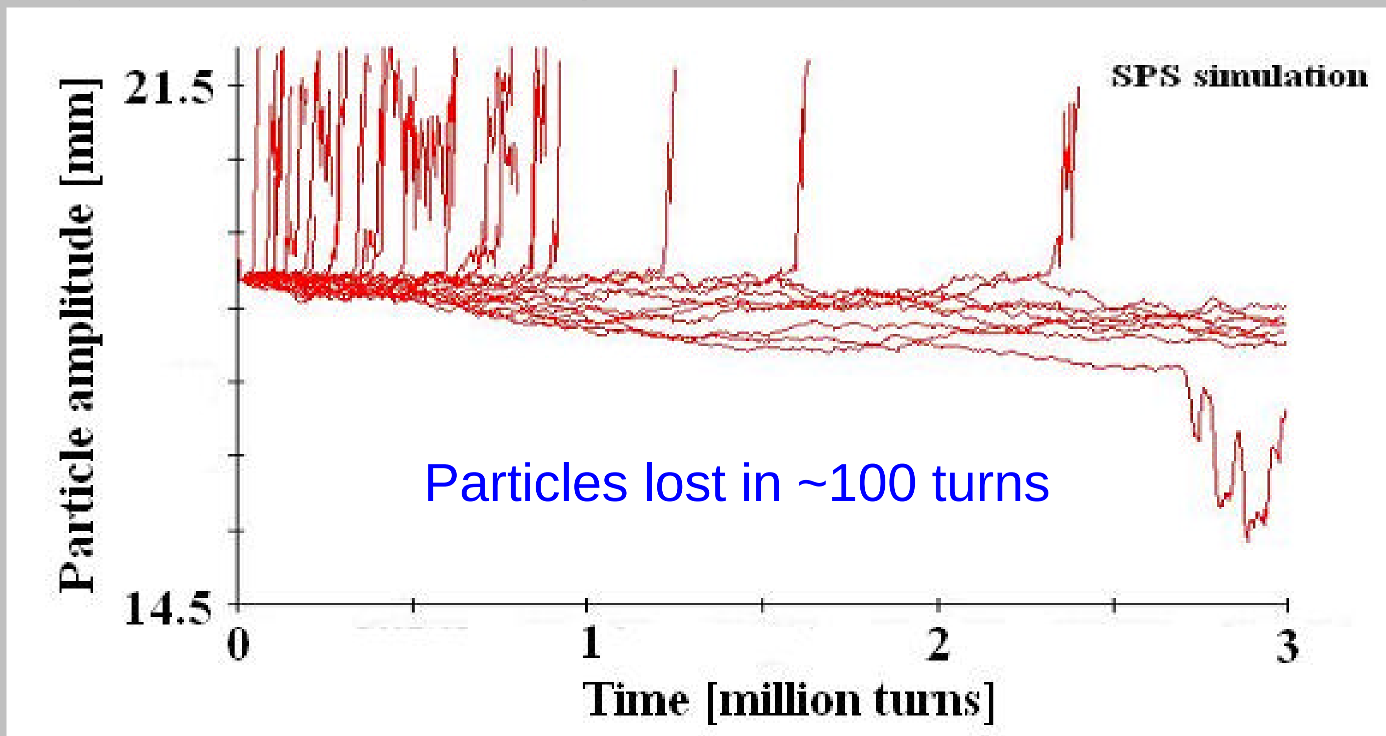


Severe problem at injection

Nonlinear fields lead to particle loss

Field errors make particle motion
at large amplitudes <u>chaotic</u>
(completely deterministic but unpredictable)

$$L(t) = \frac{1}{4p} f_0 N \frac{n^2(t)}{s^2_{rms}(t)}$$



Simulations determine tolerable magnet errors (since ~10 years)
Important during design stage

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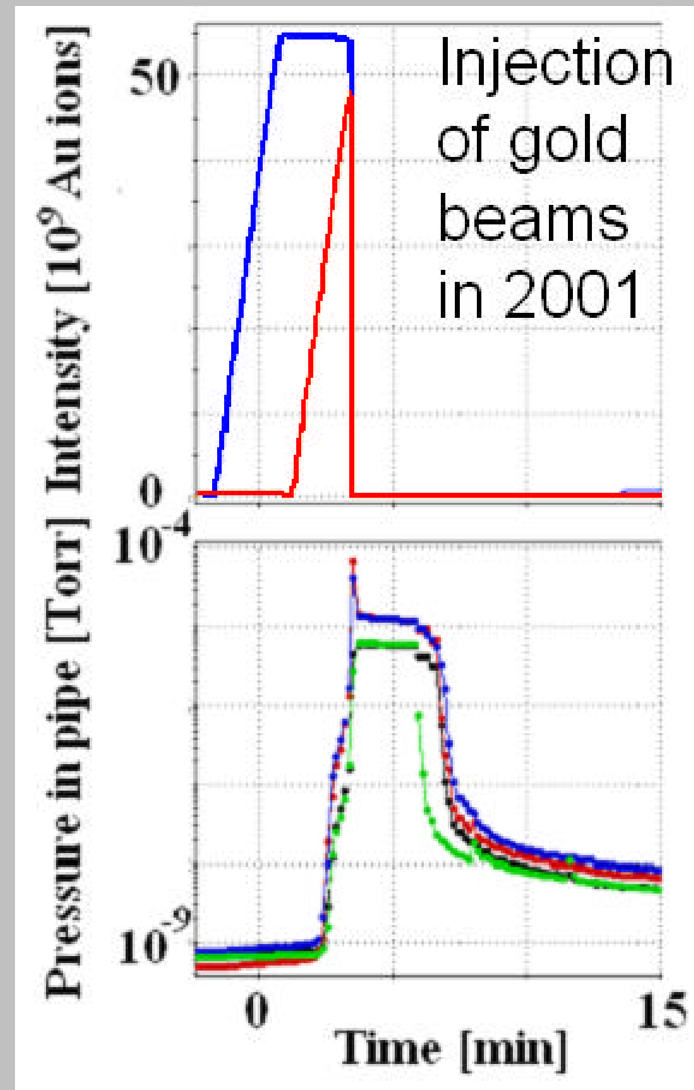
Large intensity raises pressure

$$L(t) = \frac{1}{4\pi} f_0 N \frac{n^2(t)}{\sigma^2_{rms}(t)}$$

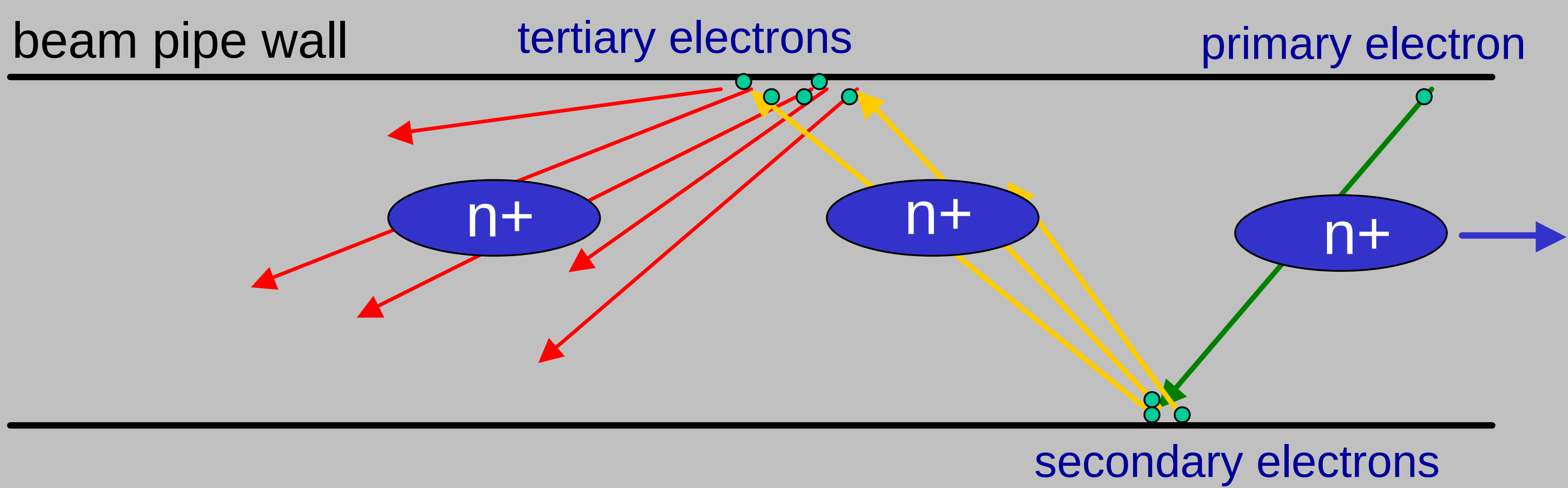
Need good vacuum in beam pipe

(otherwise too many beam particles are lost after collision with rest gas molecules)

Beam can destroy good vacuum



Beam forms electron cloud …

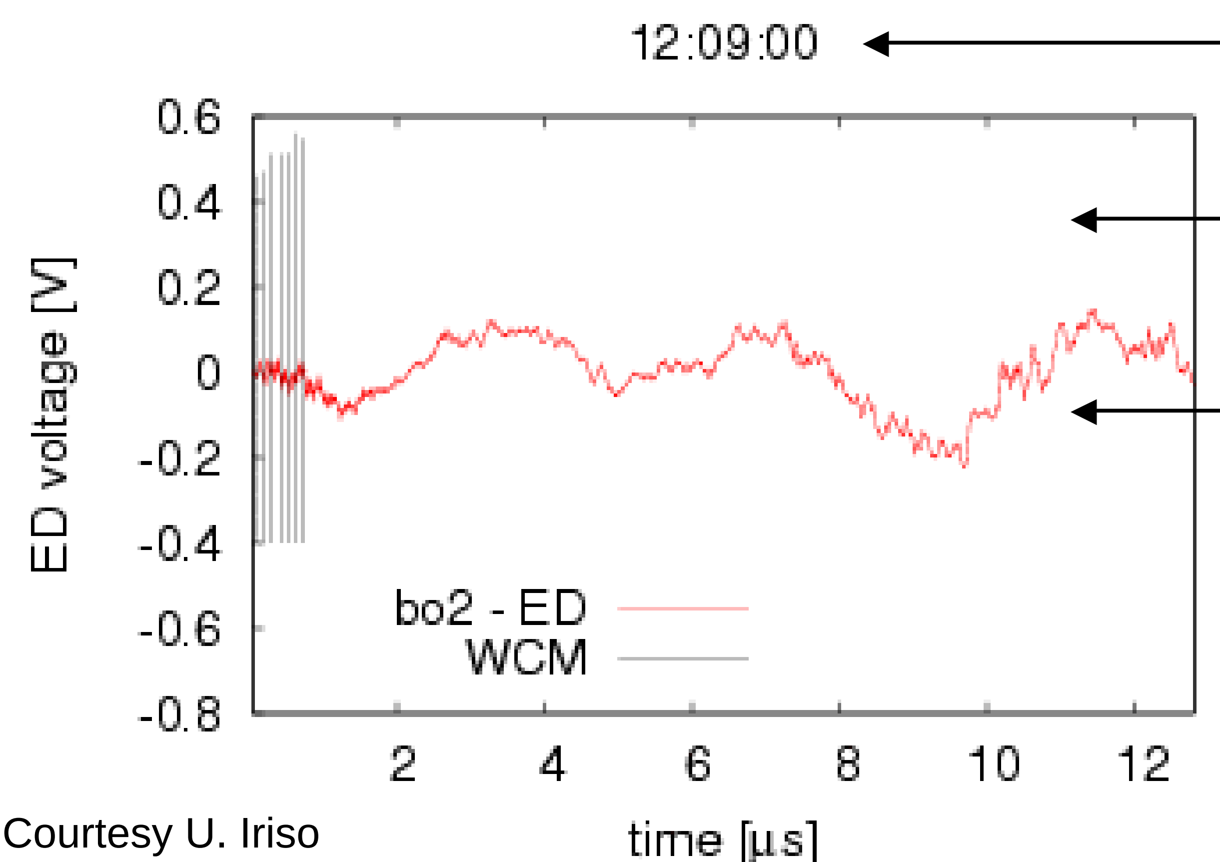


Electrons hitting the wall also desorb molecules

about 1 molecule for every 1000 electrons

® **pressure rise**

E-cloud formation at injection



Courtesy U. Iriso

time

buches being filled

electon cloud density
(red line)

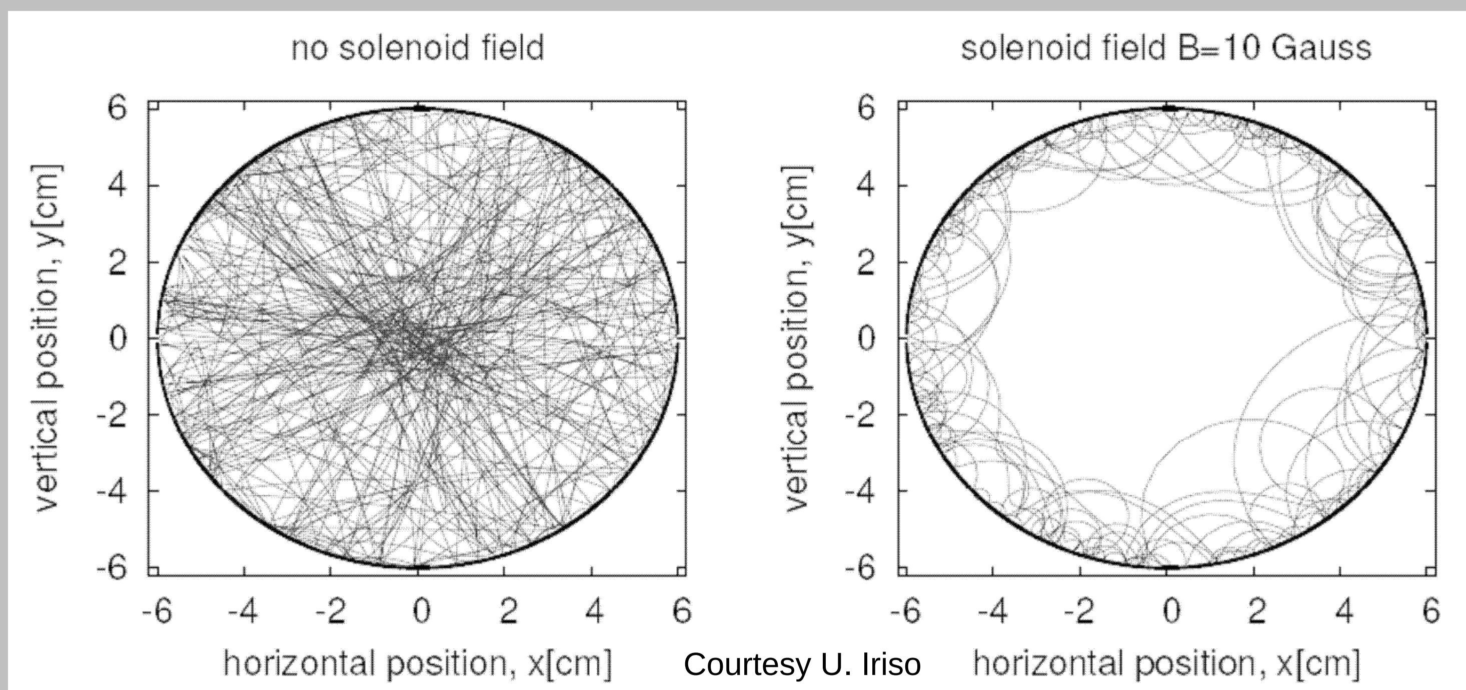
Electron cloud suppression

- **Optimum bunch distribution**
- **Coated beam pipes** – main strategy for RHIC

non-evaporable getter material (NEG) – has low secondary electron yield, distributed pumping

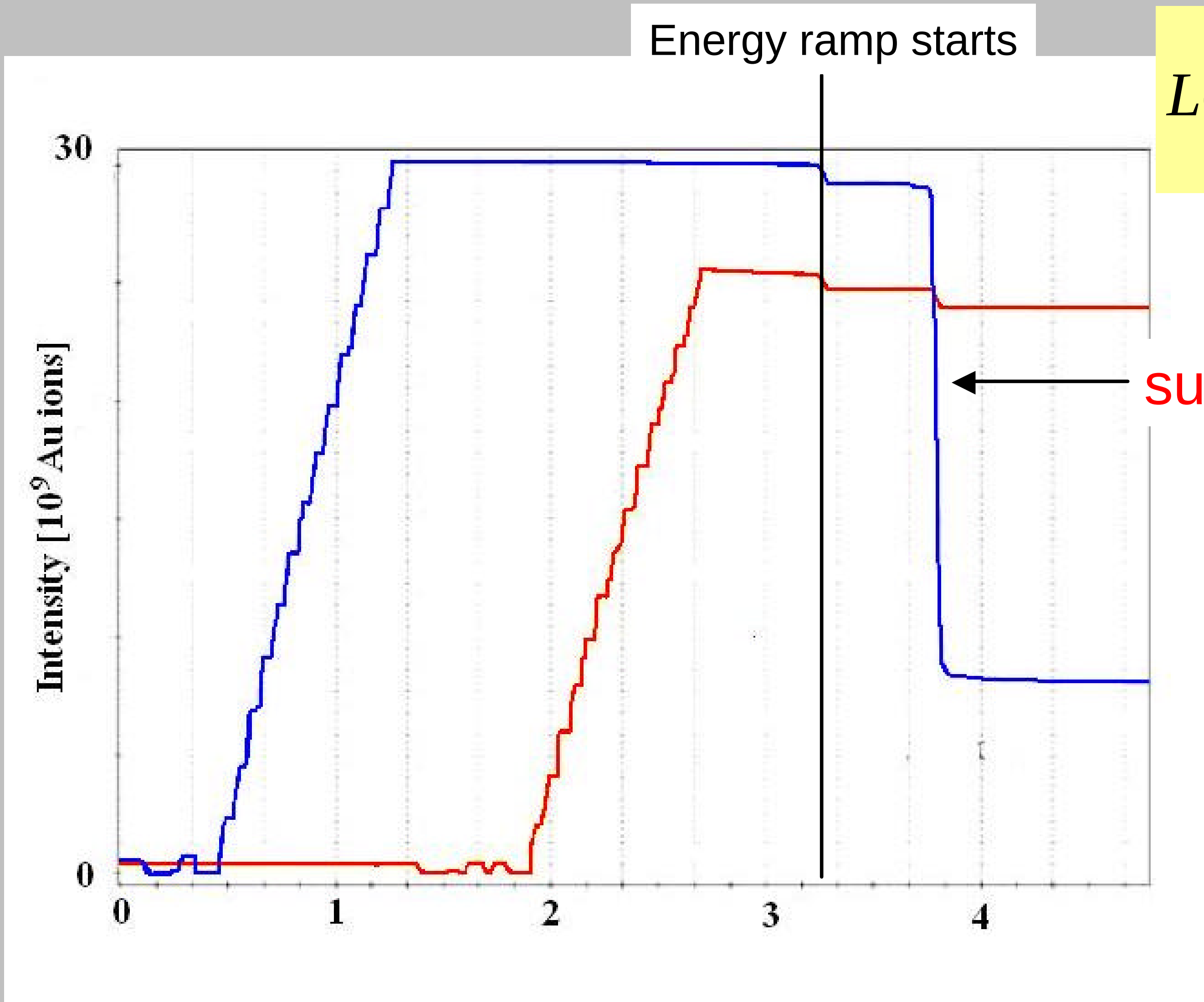
- **Solenoids** – in selected areas

pin down electrons at beam pipe wall – cannot multiply



Courtesy U. Iriso

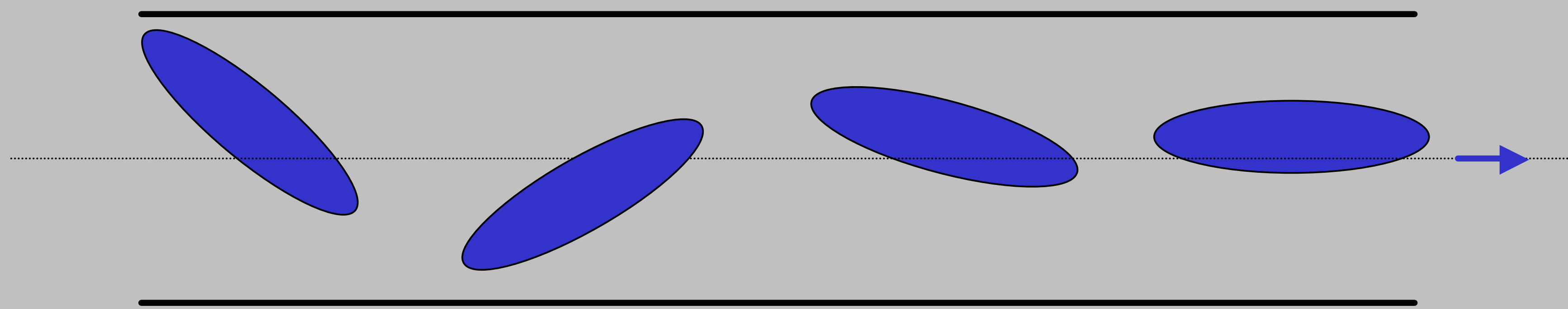
Instabilities limit bunch intensity



$$L(t) = \frac{1}{4p} f_0 N \frac{n^2(t)}{s_{rms}^2(t)}$$

Instabilities limit bunch intensity

Resistive beam pipe wall …



… can make a bunch tail unstable.

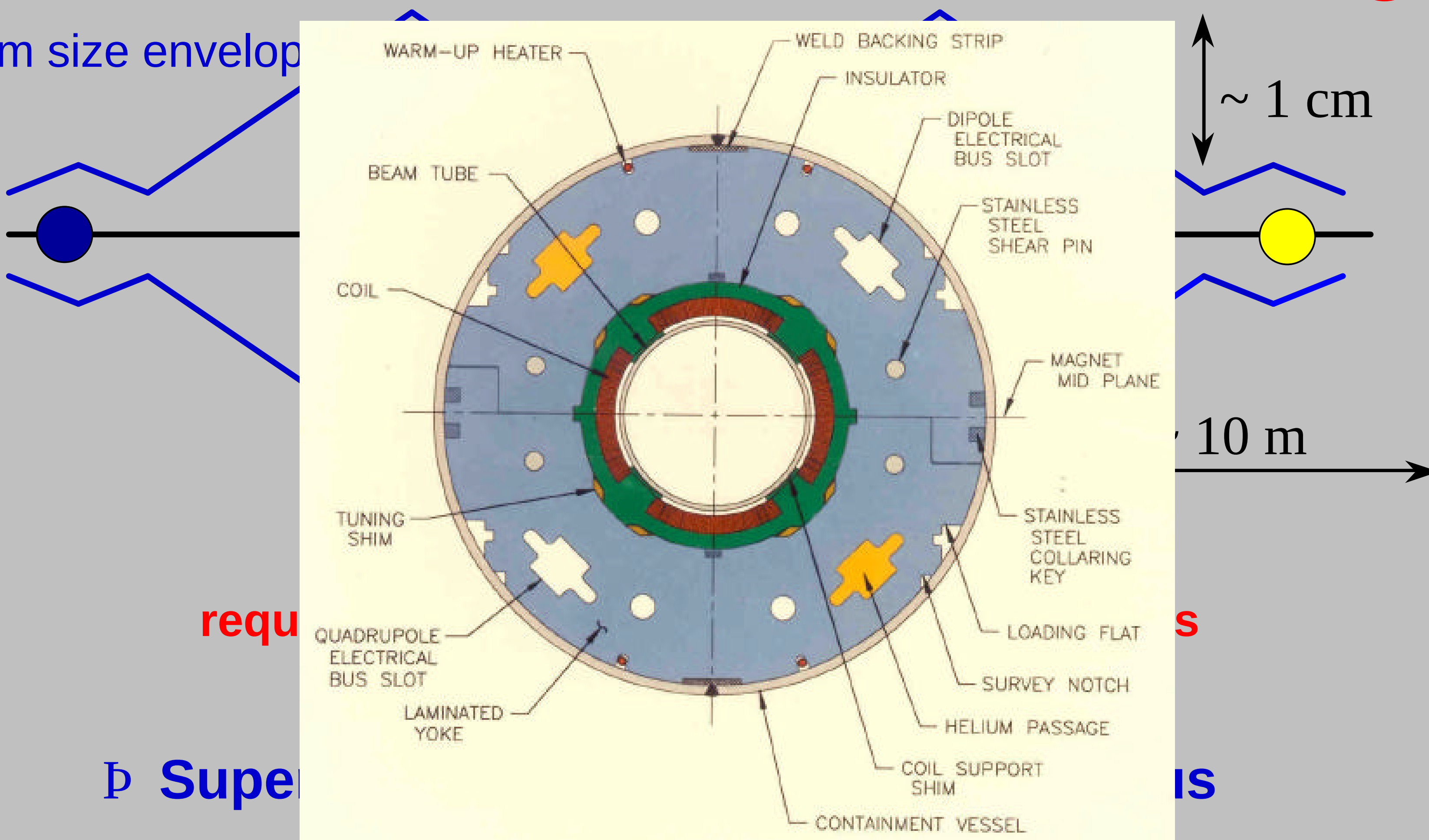
Can be suppressed with

- **sextupole and octupole magnets**
- **feedback systems**

Final focus system limits σ

$$L(t) = \frac{1}{4\pi} f_0 N \frac{n^2(t)}{\sigma_{rms}^2(t)}$$

Beam size envelop

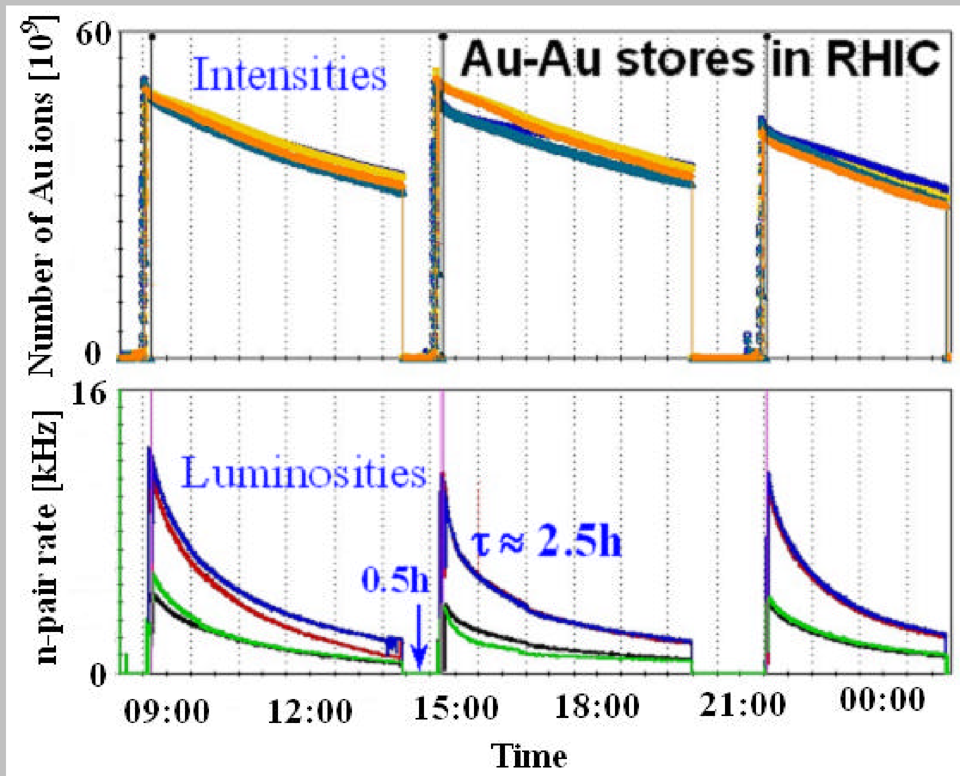


requ **s**

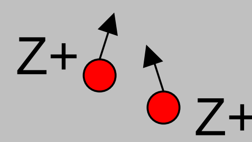
Þ Super **us**

Field errors in sc magnets lead again to chaotic particle motion, need correction magnets

Intrabeam scattering increases beam size



$$L(t) = \frac{1}{4\pi} f_0 N \frac{n^2(t)}{\sigma_{rms}^2(t)}$$

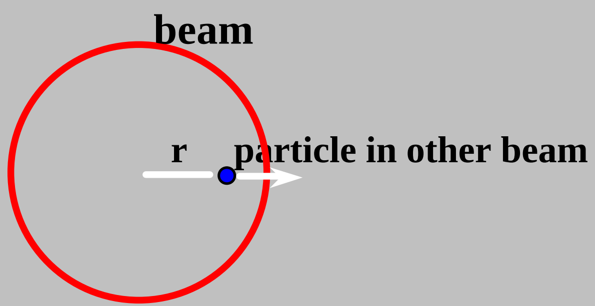


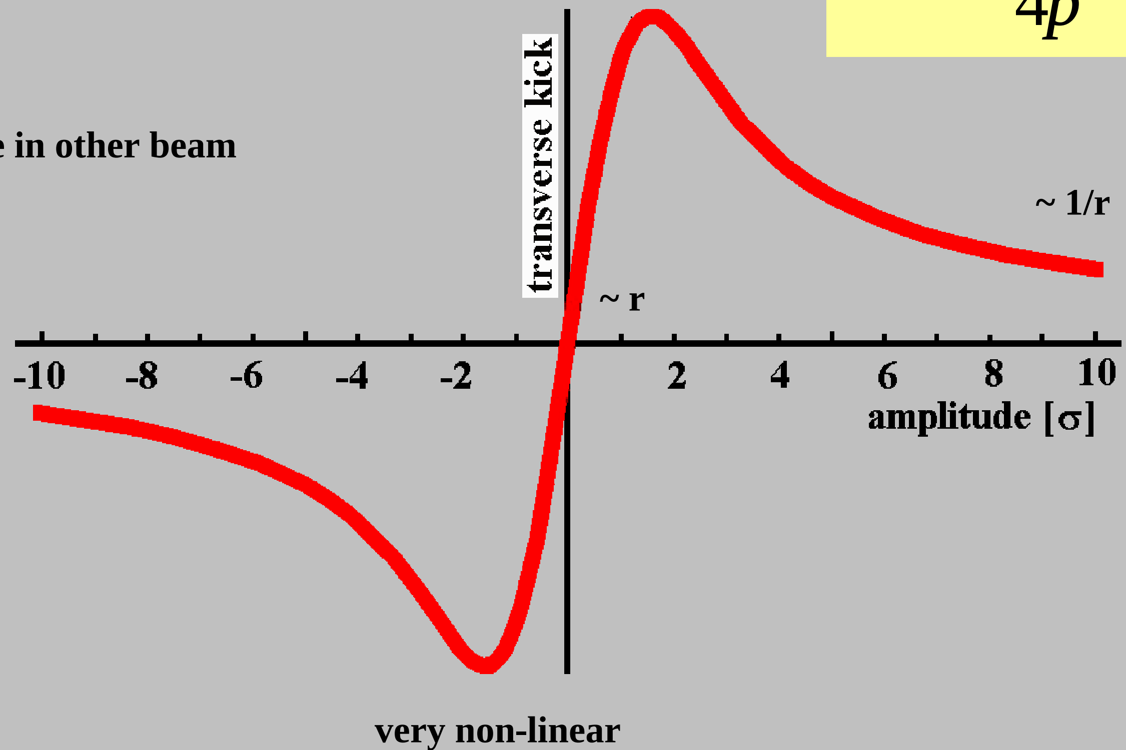
Scattering of particles within bunch leads to
- beam size growth
- particle loss

Strongly dependent on ion charge state Z
- very severe for Au^{79+}
- 10x less severe for p^+

Beam-beam effects limit n/σ^2

$$L(t) = \frac{1}{4p} f_0 N \frac{n^2(t)}{s^2_{rms}(t)}$$

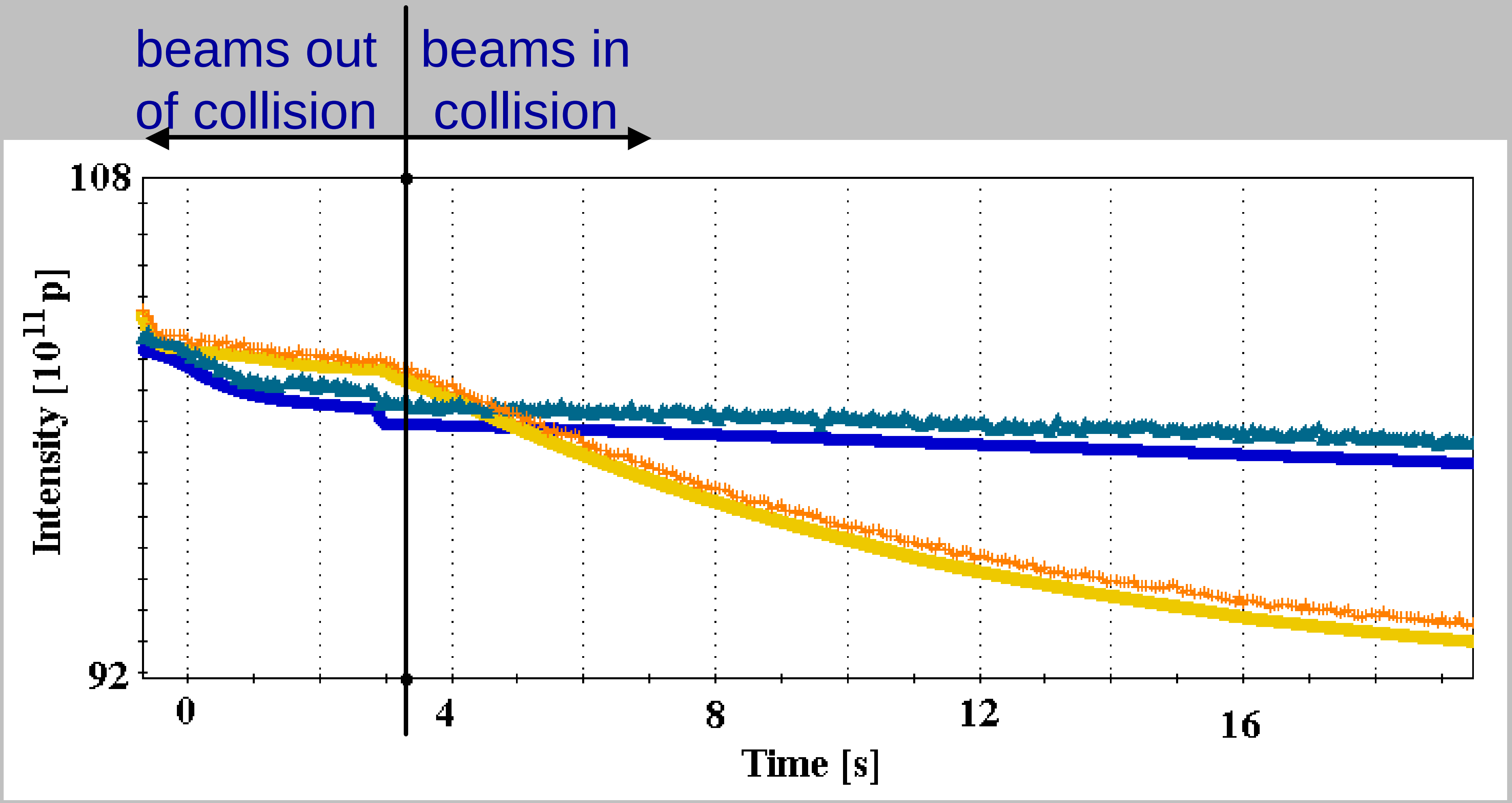




Beam-beam interaction also leads to chaotic particle motion

- Beam size growth
- Beam loss

Beam-beam effects limit n/σ^2

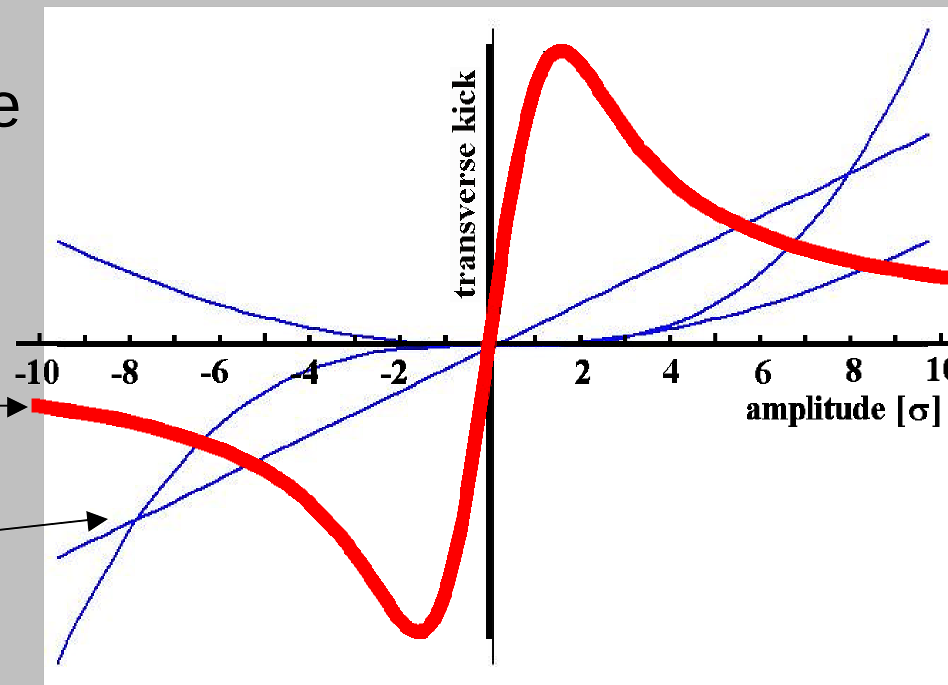


Beam-beam effects limit n/σ^2

Beam-beam effects cannot be corrected with magnets

beam-beam kick

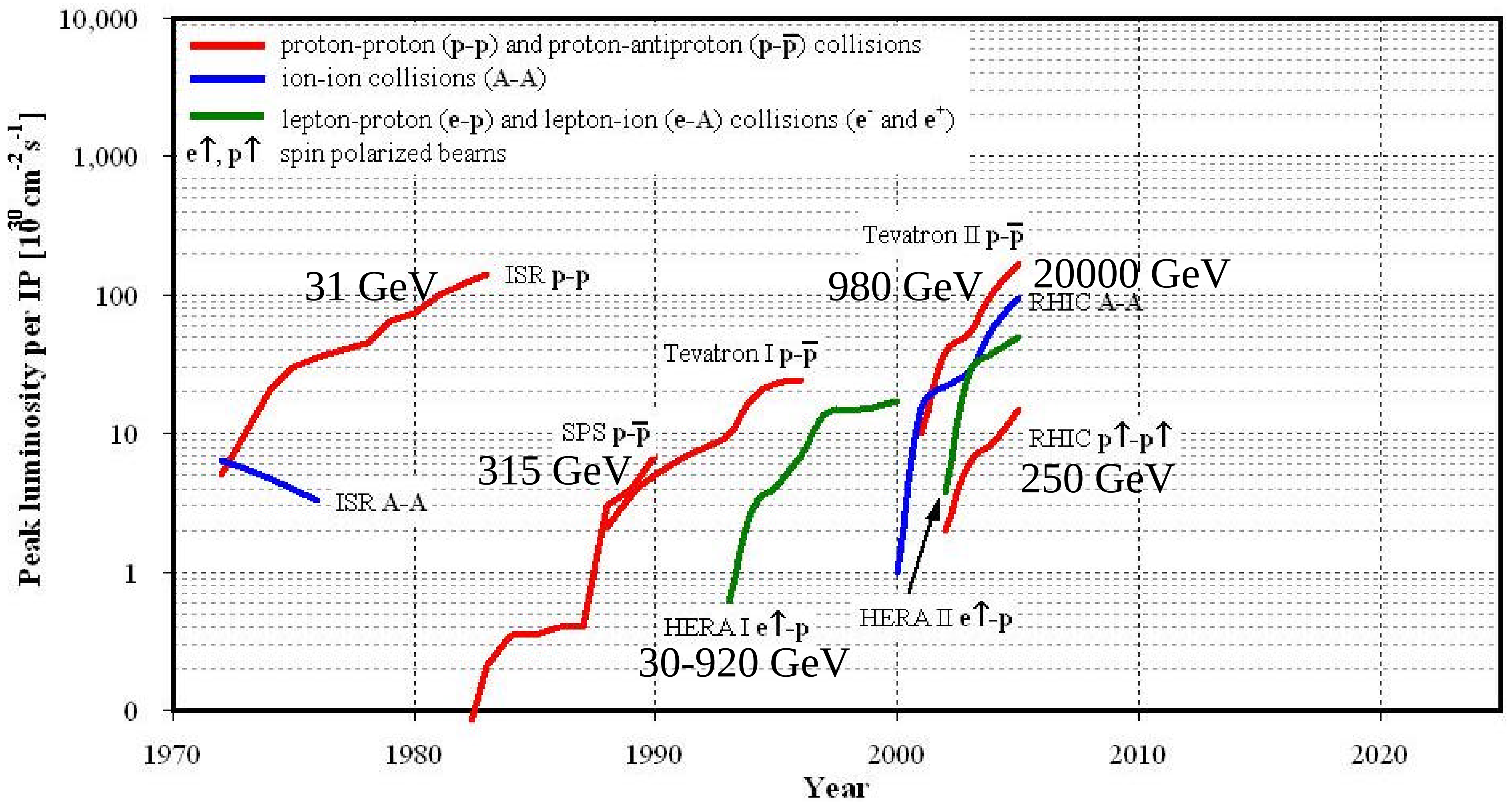
magnet kicks



- To compensate beam-beam effect, need an electron beam
  Not successful so far …
- To simulate of beam size growth, need supercomputers (~Tflops)
  Not successful so far …

General strategy:
minimize all other nonlinearities and sources of noise

The Quest for **High Luminosity** in **Hadron Colliders**



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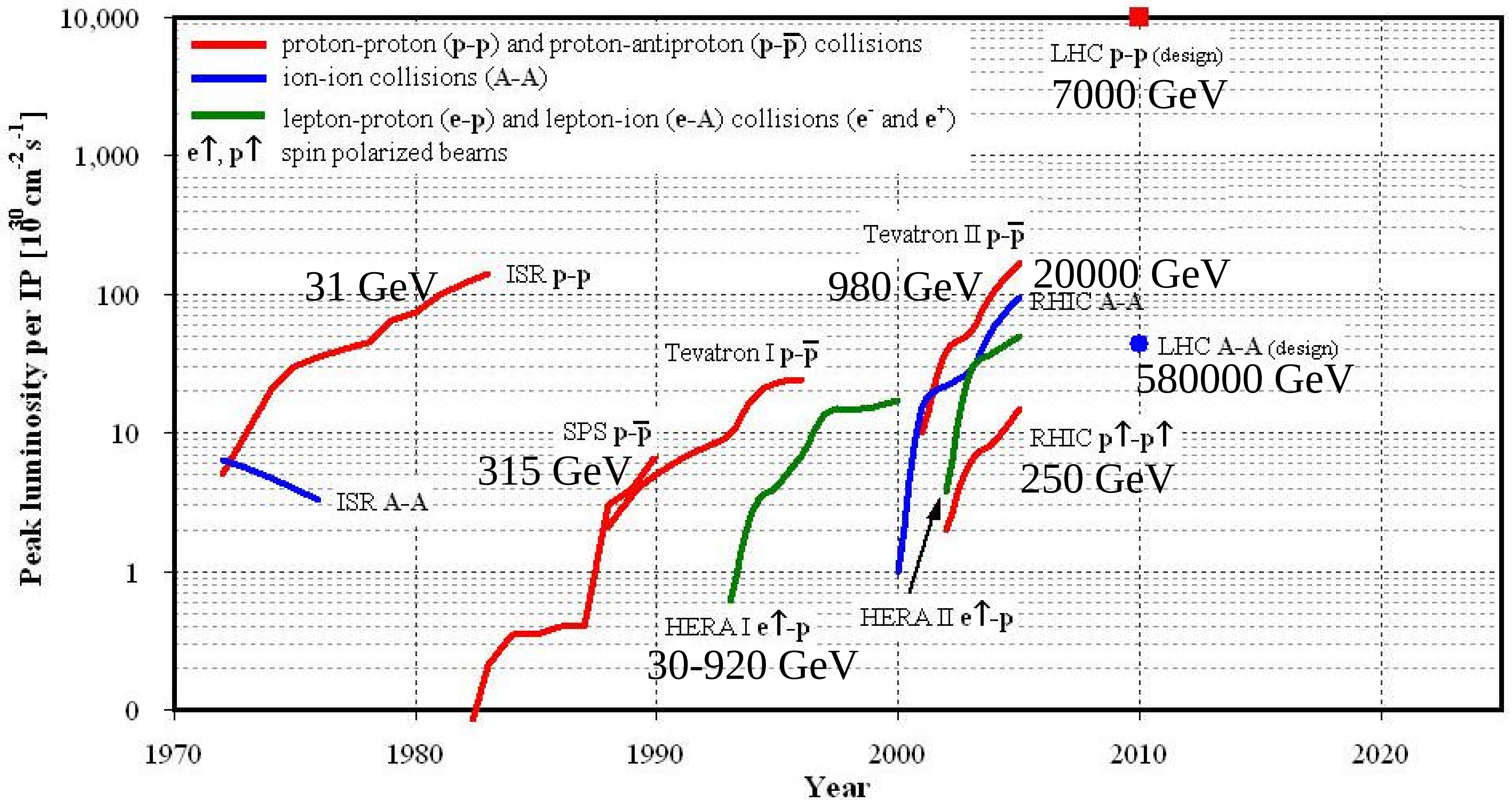
The Quest for **High Luminosity** in **Hadron Colliders**



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CERN – Large Hadron Collider (LHC)

Time	2007-
Circumference [km]	26.7
Energy [GeV]	7000 p 580000 Pb
Particles	p-p Pb-Pb
Peak luminosity [10^{30}cm^{-2}s^{-1}]	**10000 (design)**

Large amount of stored beam energy (350MJ)
Almost every beam dynamics problem relevant

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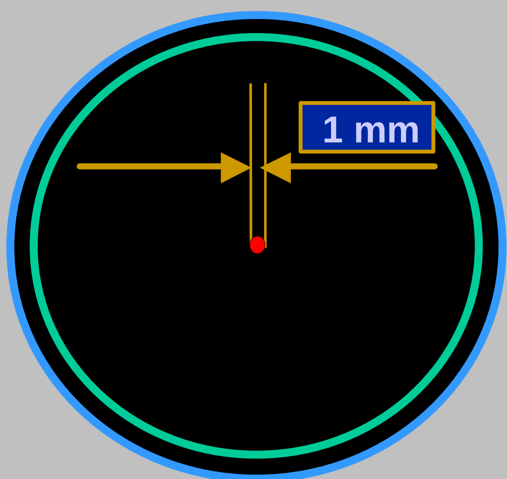
CERN – Large Hadron Collider (LHC)

Beam size in beam pipe

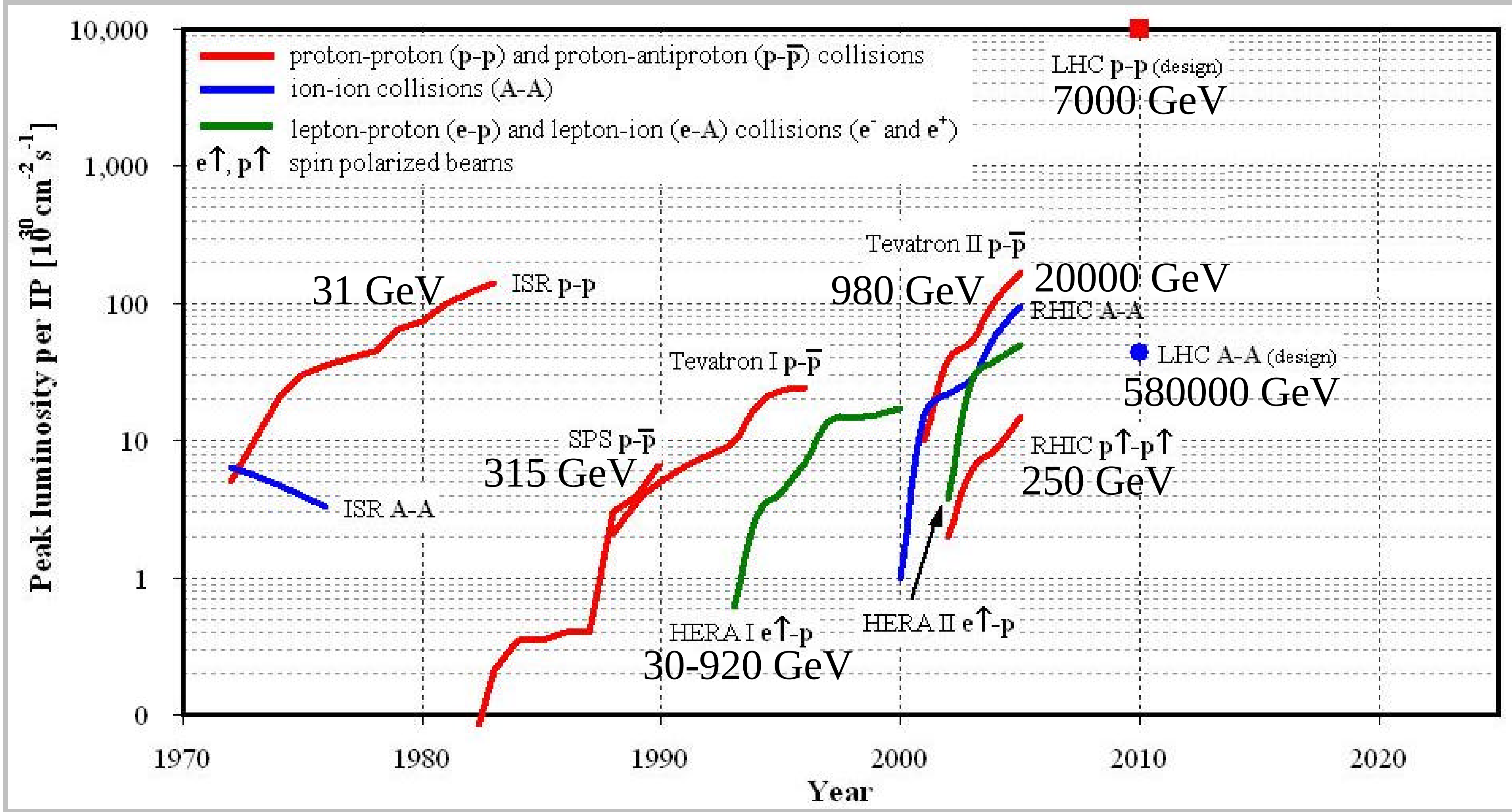


350MJ stored energy per beam

= kinetic energy of 20 fully loaded class 8 trucks (120,000lbs) at 55mi/hr

Must avoid large beam losses in limited time and space

The Quest for High Luminosity in Hadron Colliders

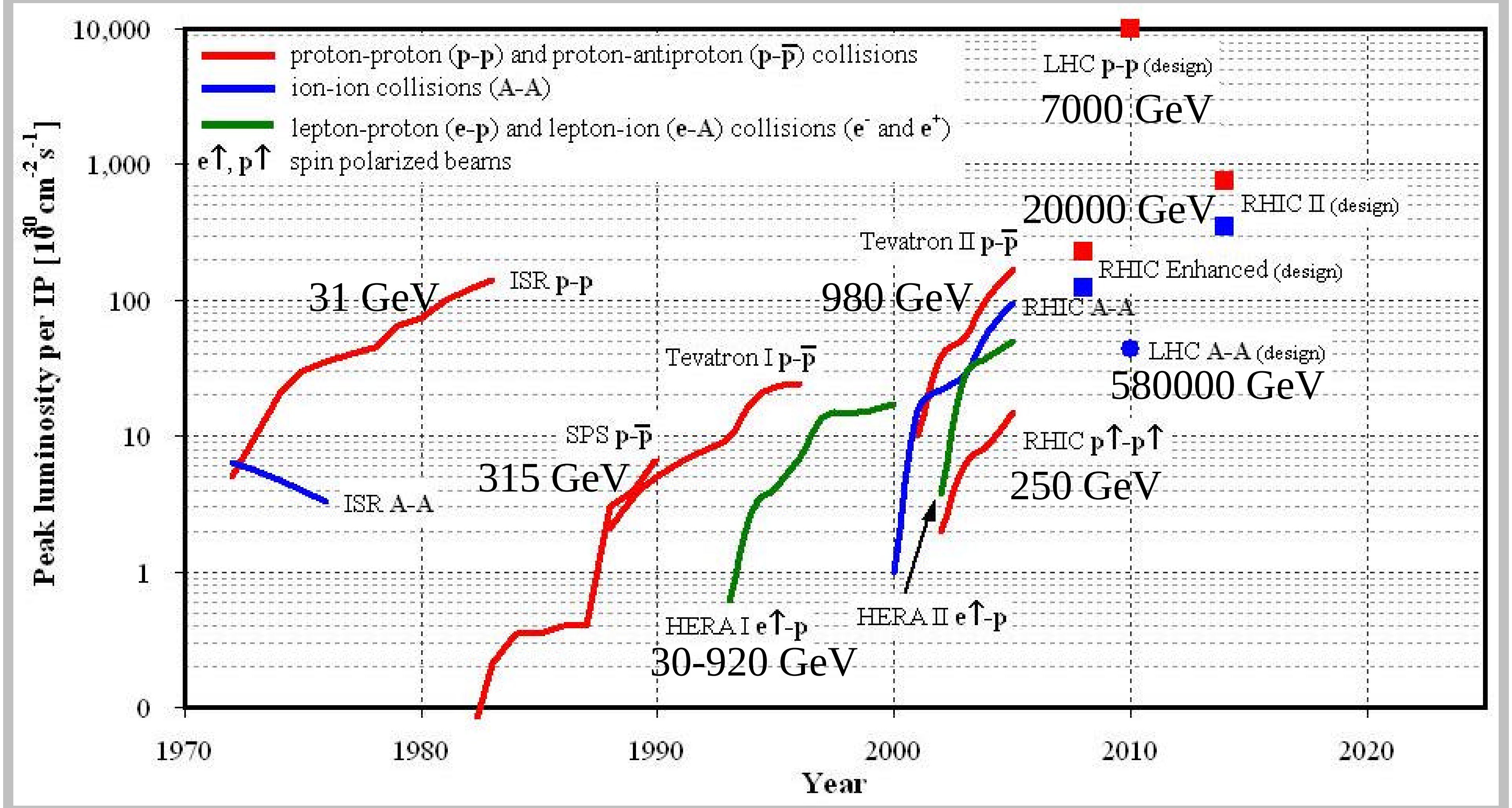


RHIC vs. LHC

The LHC will have higher collision energies, but RHIC will have:

- Higher heavy ion luminosity
- More flexibility for parameter scans
  (species, energies)
- More heavy ion running time
  (only 4 week/year for heavy ions in LHC)
- <u>Polarized</u> protons

The Quest for **High Luminosity** in **Hadron Colliders**



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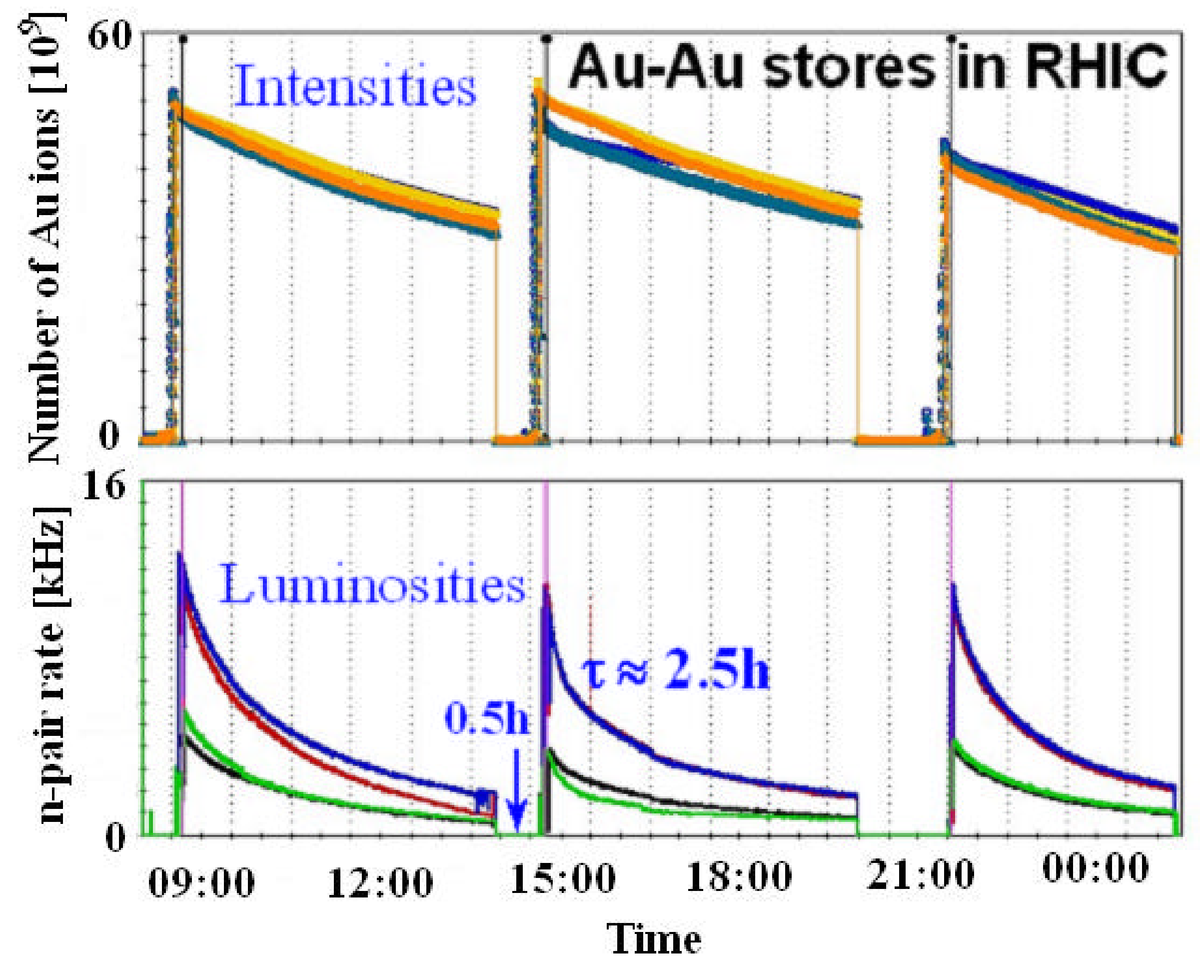
RHIC II (e-cooling) [≥ 2012]



Heavy ion beam loss and beam size growth dominated by

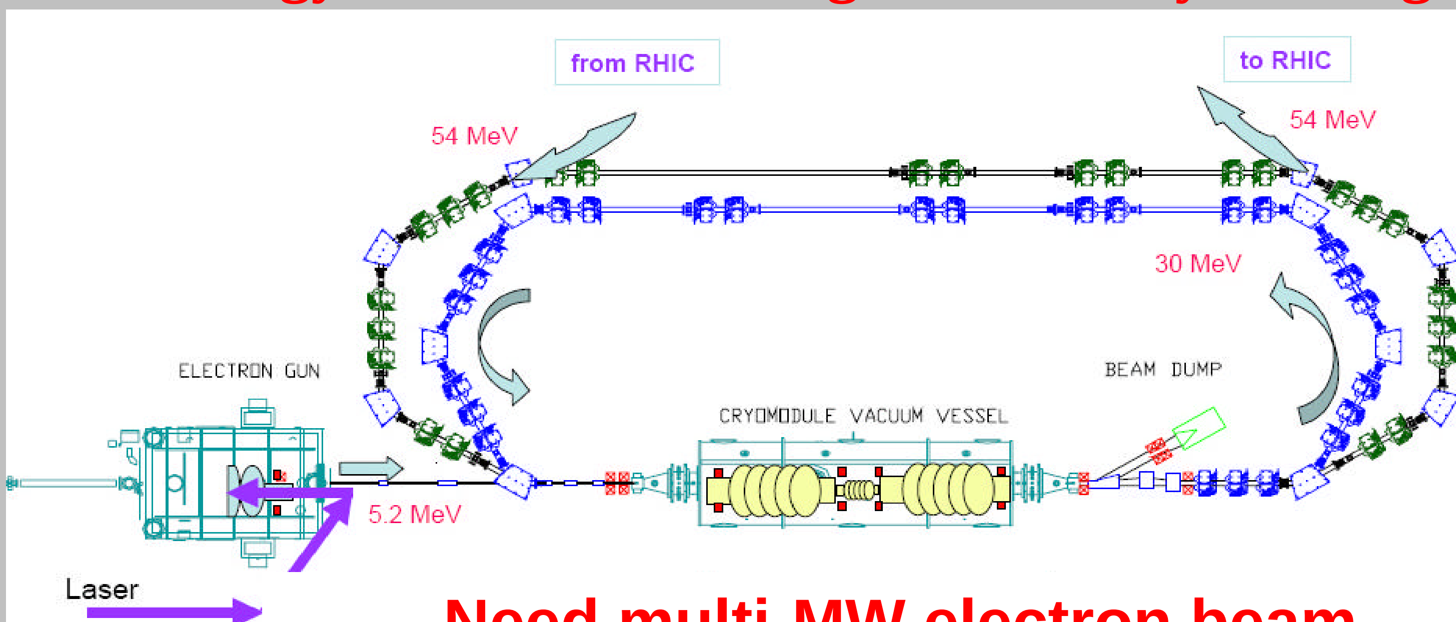
intrabeam scattering

Can only be overcome by beam "cooling"

RHIC II (e-cooling) [≥ 2012]

Electron cooling:
submerge "hot" ion beam in "cold" electron beam

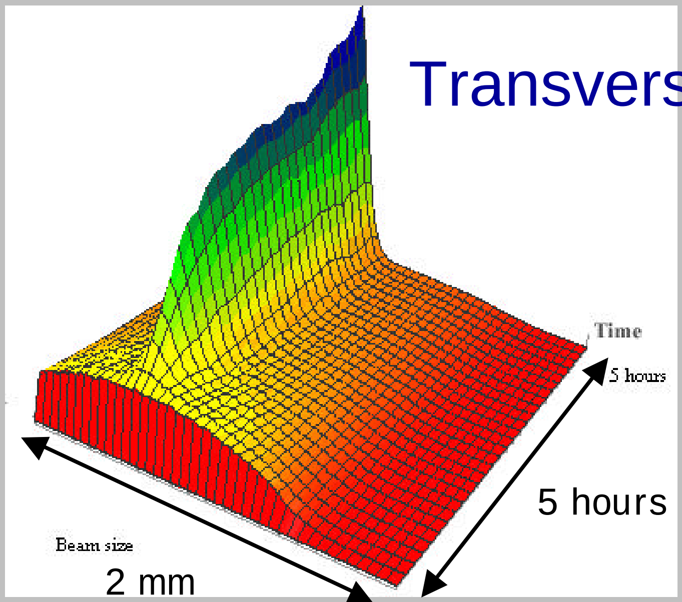
- **1st time in a collider**
- **beam energy more than 10´ higher than any existing cooler**



Need multi-MW electron beam prepared with an Energy Recovery Linac

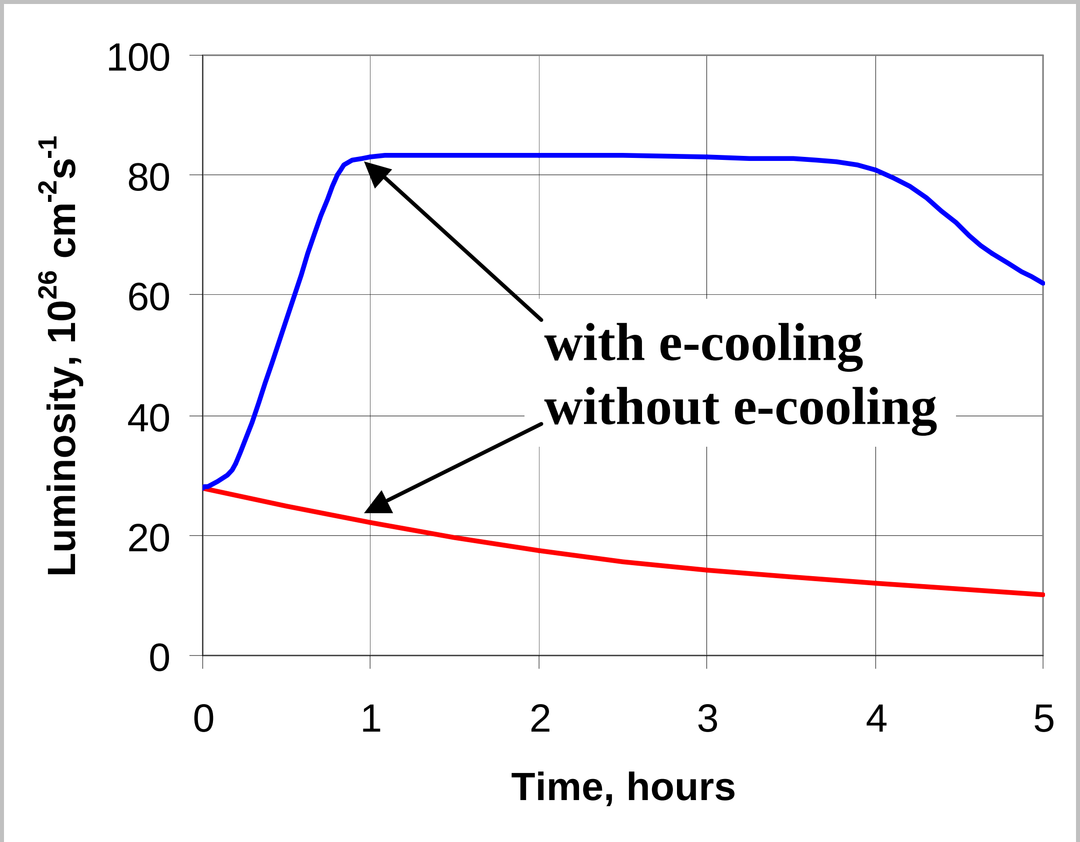
I. Ben-Zvi, 380th Brookhaven Lecture

RHIC II (e-cooling) [≥ 2012]



Transverse beam profile in store

Only works for heavy ions in store



Store length limited to
4 hours by "burn-off":
Dominant beam loss
from particle collisions

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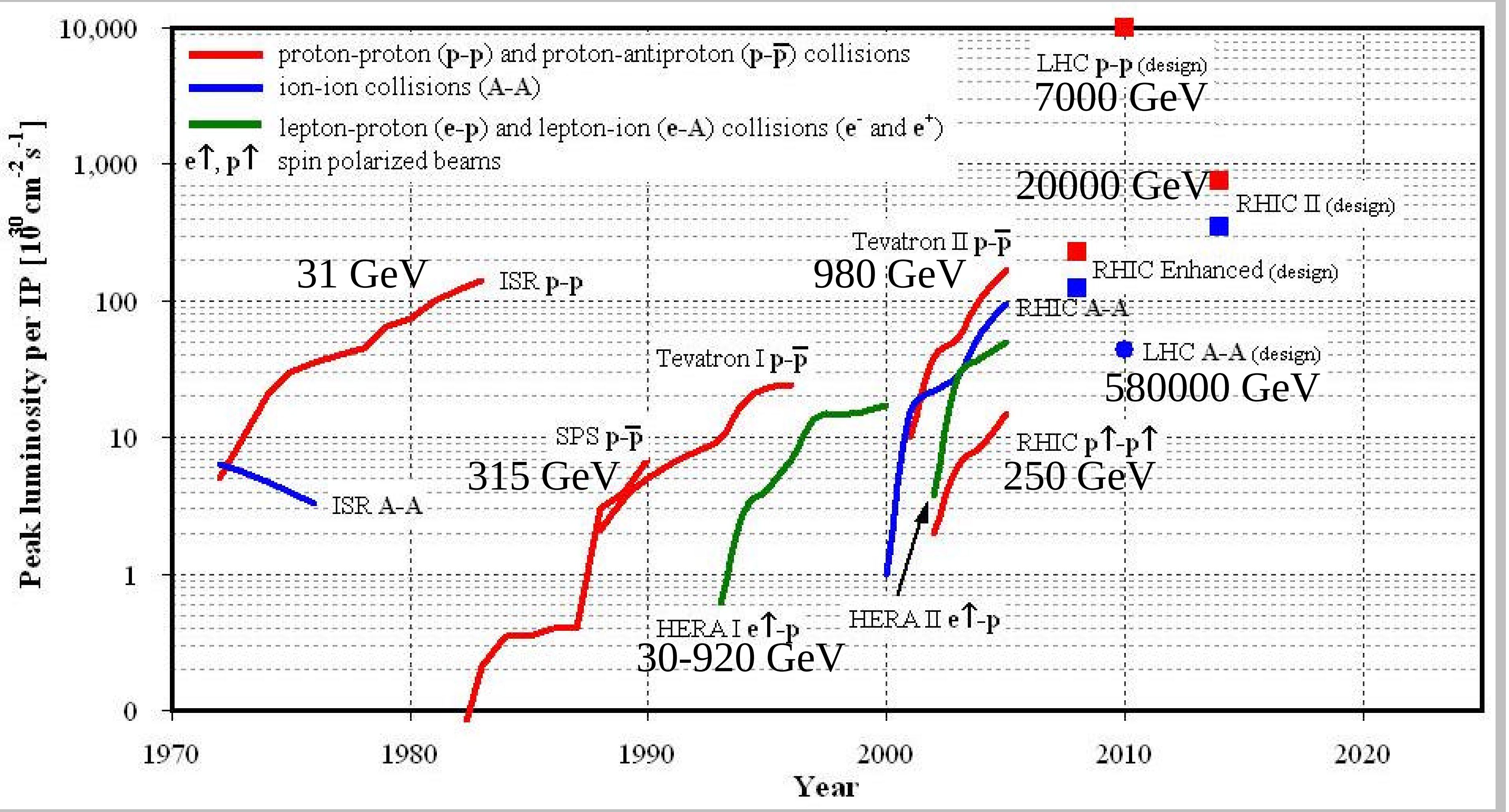
The Quest for **High Luminosity** in **Hadron Colliders**



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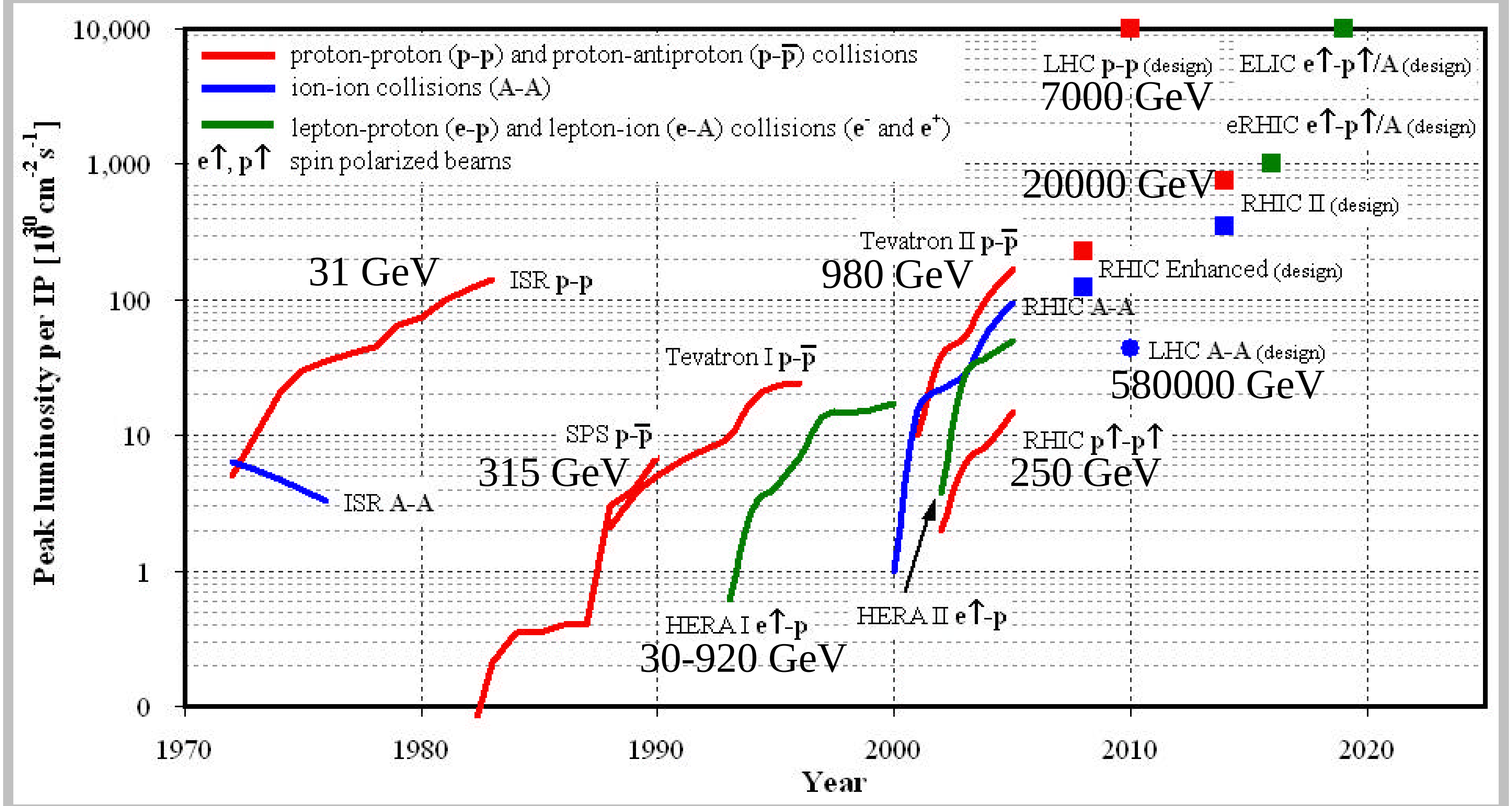
The Quest for **High Luminosity** in **Hadron Colliders**



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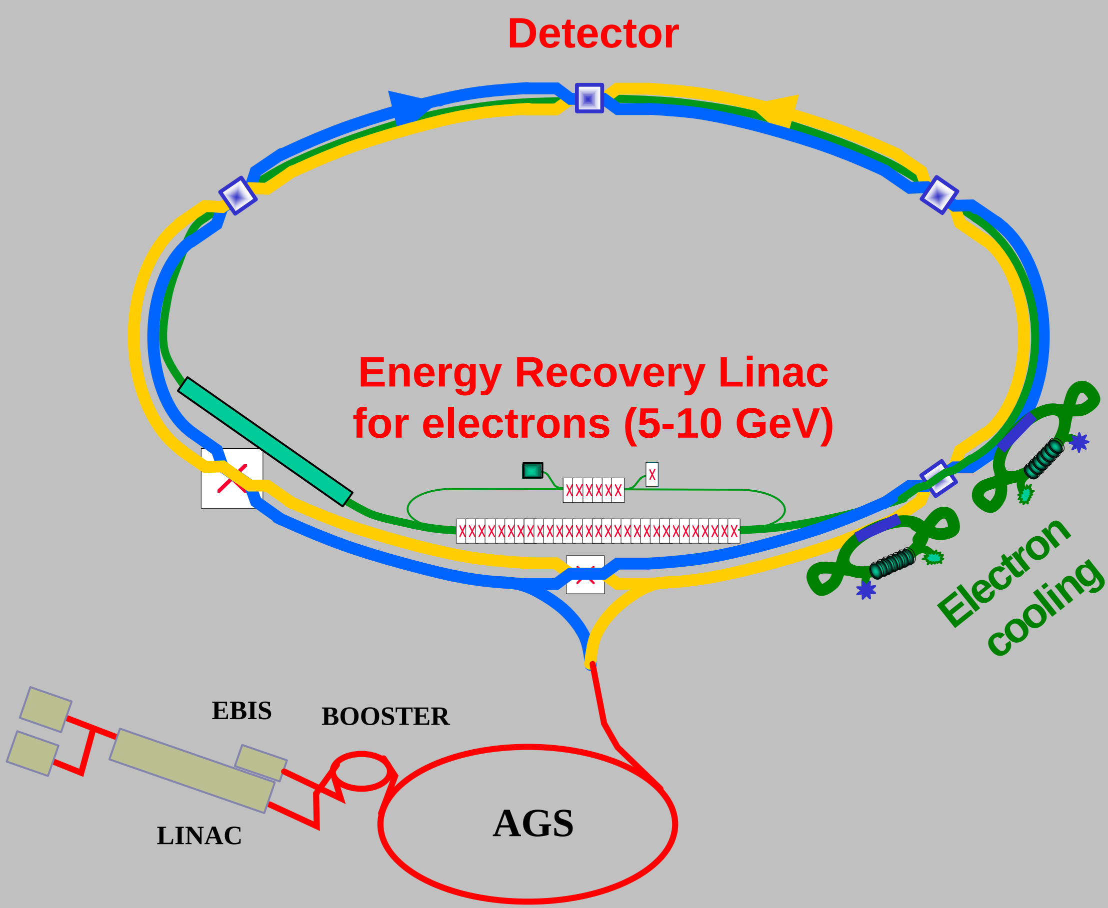
RHIC upgrades – eRHIC [≥ 2014]



Main design parameters

- center-of-mass energy
  30-100 GeV/n
- e-p luminosity
  10^{32}-10^{34} cm^{-2}s^{-1}
- e-Au luminosity
  10^{30}-10^{32} cm^{-2}s^{-1}
- polarized
  electrons, protons,
  possibly light ions

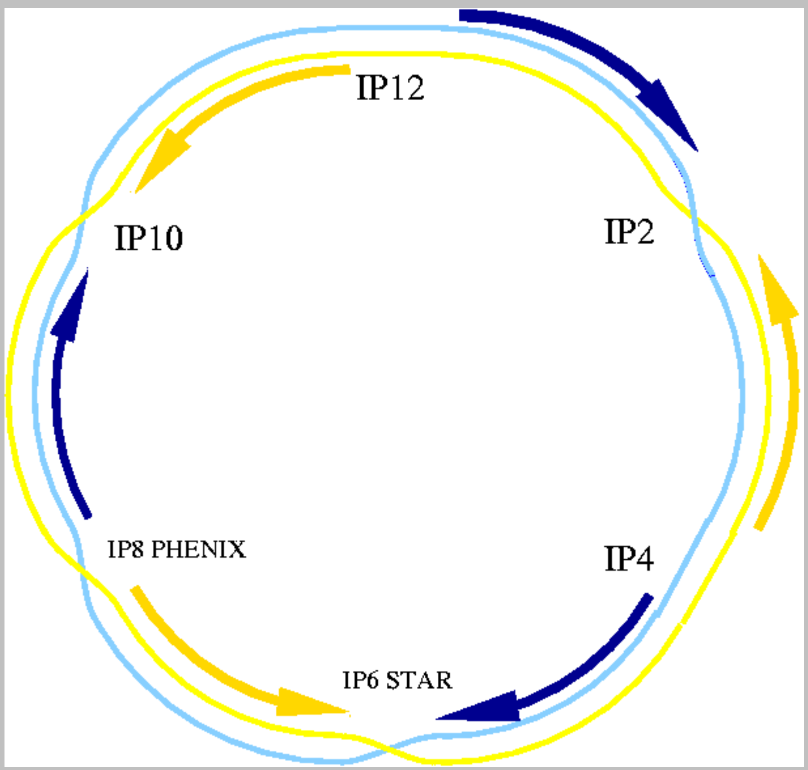
V. Ptitsyn, 405th Brookhaven Lecture

Beyond RHIC II – “SuperRHIC”

- What is the ultimate Au-Au luminosity?
- What is the ultimate p-p luminosity?

Beyond RHIC II – "SuperRHIC" Au-Au

- Au beam loss with e-cooling dominated by burn-off
  (particle loss from collisions studied by experiments)
- Luminosity increase only with more beam of same density
  (other methods only lead to faster burn-off)



® **Superbunches**
(very long bunches)

® Need different acceleration technique (R&D item)

3 long bunches fill
1/2 of circumference
(currently 4% filled)

Au Luminosity increase of ~15x

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Beyond RHIC II – “SuperRHIC” p↑-p↑

- p beam loss dominated by beam-beam interactions
- e-cooling at store not effective

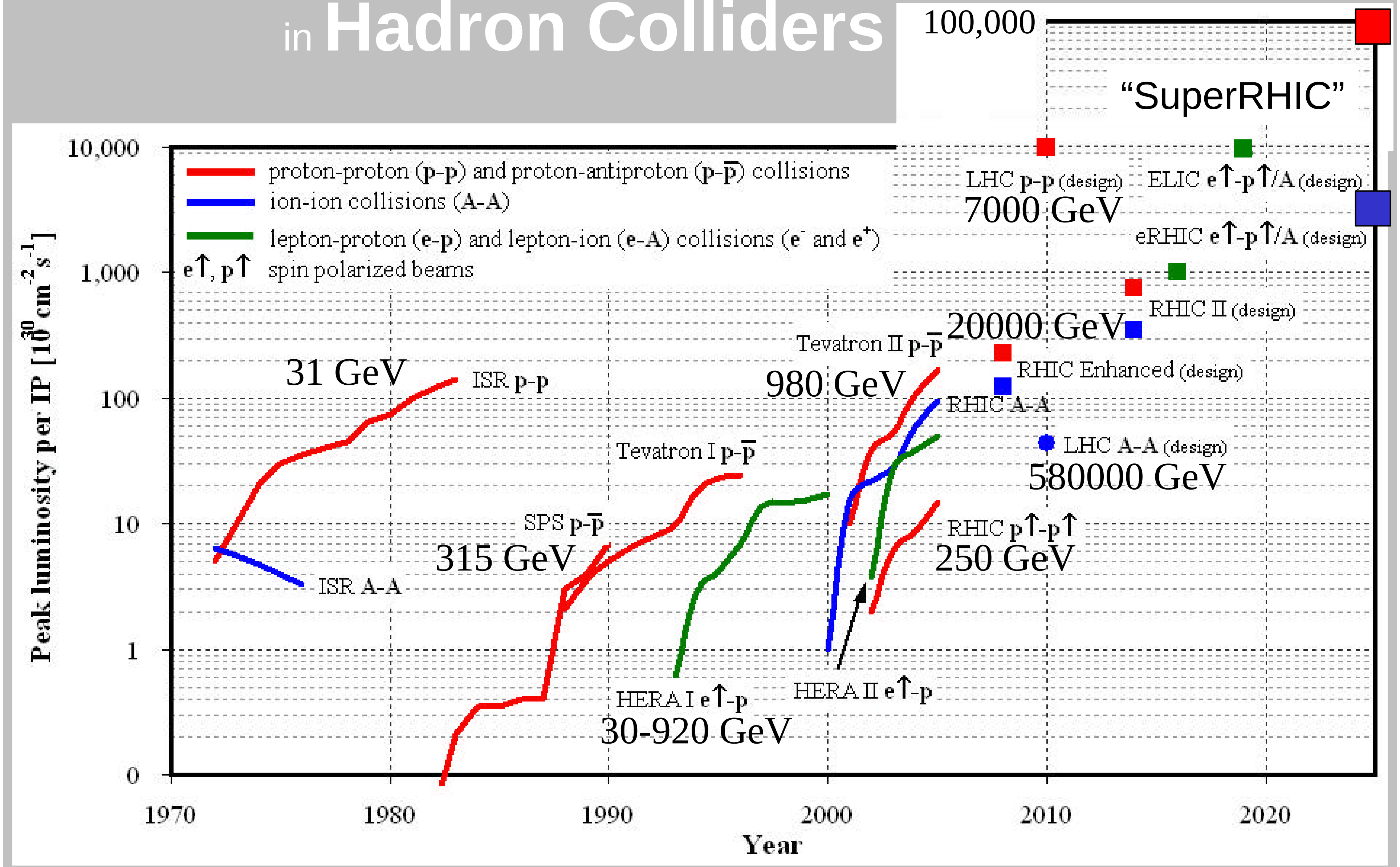
Need new ideas:

1. Superbunches
2. Electron lenses compensate beam-beam effect
3. Optical stochastic cooling at store
   (V. Yakimenko, 408th Brookhaven Lecture)

All these things are unproven technologies today,
but every new technology was at some point.

p↑-p↑ **luminosity increase of ~130x beyond RHIC II**

The Quest for High Luminosity in Hadron Colliders



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The Quest for **High Luminosity** in **Hadron Colliders**

Thank you

Wolfram Fischer
Collider-Accelerator Department